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Testing and Evaluation of Automotive Propane Conversion Equipment:3

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ABSTRACT

A series of tests has been carried out on a FORD V8 6.1 (370 CID) LIMA engine to evaluate a selected number of propane carburetion systems - IMPCO, BEAM and AFS - embodying various principles of design. The criteria used for comparison were engine output power, fuel economy and emissions. A new carburetion system design, the OXIN, was included in the evaluation. The general results indicate that, similar to previous studies, output power is close or equal to the power developed using gasoline and the fuel efficiency is generally improved by 10.8 to 21.0% for the best systems. Through optimization of air-fuel ratio and timing, a further improvement of energy efficiency between 3.4 and 18.3% was achieved by our laboratory.

1. INTRODUCTION

The Ministry of Transportations and Communications for the Province of Ontario (MTC) has contracted with the Engine Research and Development Laboratory of the Department of Mechanical Engineering, University of Toronto (ERDL/UTME), to undertake a long range and comprehensive investigation of the use of propane as an alternative fuel in internal combustion engines. This initiative of MTC arose from the Province's stated aim to displace 10% of the total transportation fuel used in Ontario by alternative fuels by 1995. This fuel demand is to be met by currently available alternative fuels of which propane would be a significant fraction.

The work to date has been directed specifically towards the evaluation of various propane conversion systems on a variety of engines, typifying the spectrum of light and medium weight road vehicles. Three models of engines have been used - a GM 3.8L (229 CID) V-6, representative of passenger cars, a FORD 4.9L (300 CID) I-6, representative of light trucks and vans and the last, with results reported in this document, a FORD 6.1L (370 CID) V-8, representative of medium trucks.

The present series of test on the FORD LIMA engine repeated the examination of the IMPCO, BEAM and AFS carburetion systems. But as well an additional evaluation was made of the OXIN system, at the request of the Ministry.

With the completion of this testing phase, a more or less complete range of investigation has been accomplished. The results provide definitive quantitative information on the performance to be expected when using properly installed and appropriately set-up propane conversion equipment in essentially unmodified internal combustion engines.

2. EXPERIMENTAL FACILITIES

2.1 Test Engine

Make: FORD

Identification: LIMA LSG861I-6005-J

Number of cylinders: V-8, OHV

Serial numbers: c-00378-S 29 TC

Bore: 101.600 mm (4 in)

Displacement: 6. 1L (370 CID)

Compression Ratio: 8:1

Carburettor: HOLLEY/MOTORCRAFT D9TE EBA
E 1G9

Distributor: 1H 07
D9 TE
12127
AUA

Spark plugs: MOTORCRAFT ASF 32

Replaced by: CHAMPION RBL 11Y

Gap: 1.14 mm (0.045 in)

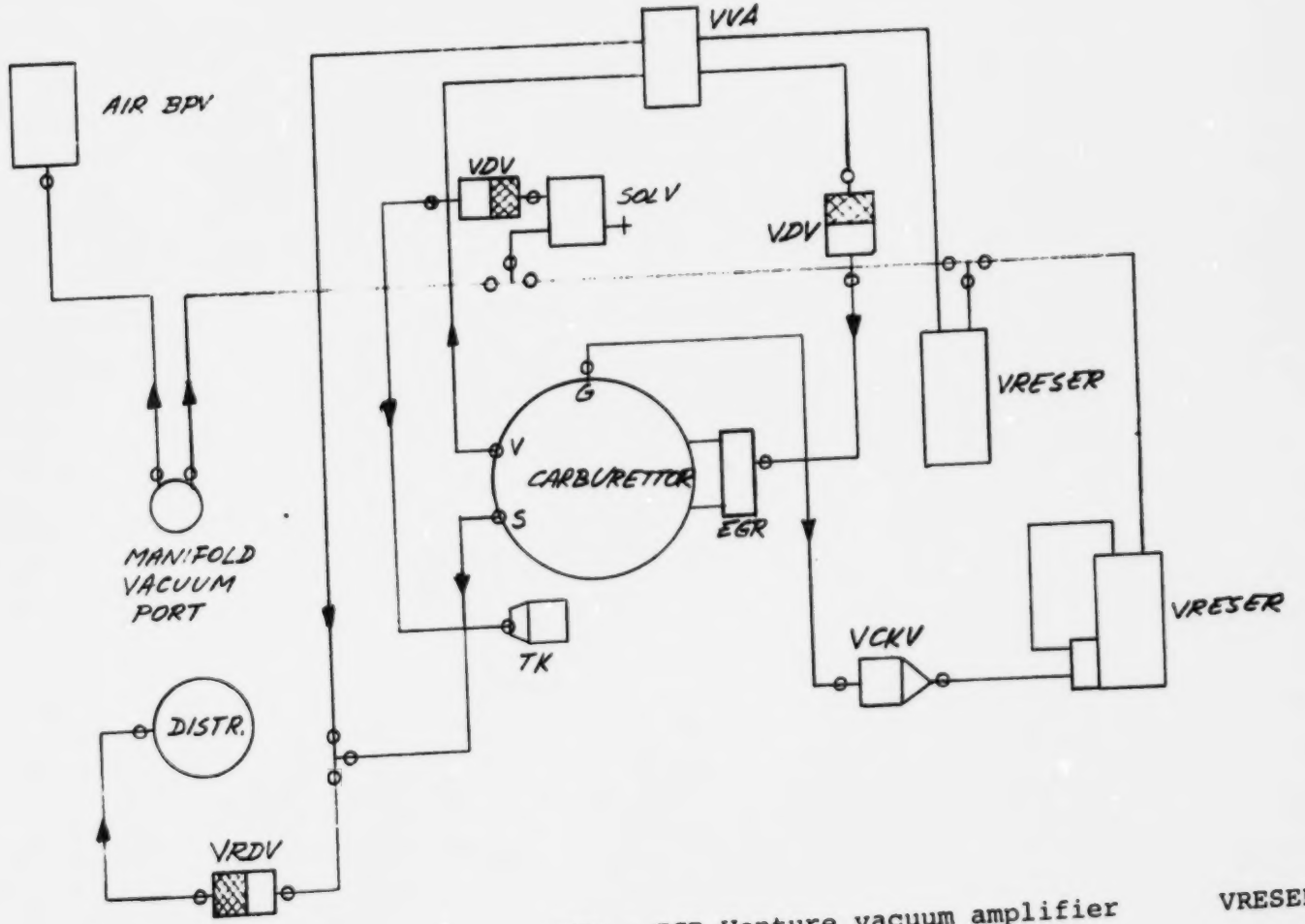
Firing order: 1-5-4-2-6-3-7-8

Emissions control system: calibration 9-83 H as in 1982 F - 600,700 vehicles - see Fig. 2-1. The engine original muffler is installed (no catalytic converter provided).

EGR valve: D8DE-9D475-C24
139

Air pump: COT EITE 2DA

Electrical system: original DURASPARK II ignition system and governor (speed control), supplied by external 12V DC. Alternator 60A E1BF 10346 AA installed and belt driven,



AIR BPV = air bypass valve
VRDV = vacuum retard delay valve
TK = throttle kicker

VVA = EGR Venture vacuum amplifier
VDV = vacuum delay valve
SOL V = TK solevoid valve
VCK V = vacuum-check valve

VRESER = vacuum reservoir

Figure 2-1: Emissions control system for gasoline.

without load.

Fan: clutch type D9HT-CA
916601 D81

Dynamometer coupling: custom flywheel to replace clutch inertia, standard bellhousing, rubber insert dynamometer driveshaft

Engine support: 4 points, rigid mount, carburettor mounting surface horizontal

2.2 Test Equipment

The models, principles of operation and the characteristics determining the precision of measurement are listed below:

2.2.1 Dynamometer: UTEE (University of Toronto Electrical Engineering) construction, model "Dynodrive 300" AC variable frequency electric dynamometer.

2.2.1.1 Torque and speed measurement: "Lebow" model 1605-5K torque (strain gauges bridge on shaft, transformer coupled to the stator) and speed (magnetic, 60 teeth) transducer.

Range: 5,000 lb. in (564, 924 N.m) N.B.: The transducer is originally rated in lb. in.

Non-linearity: 0.1% FS

Temperature effect-on zero: 0.2 F.S./100°F
-on signal: 0.2 of reading/100°F

Compensated temperature range: 50 to 150°F

Calibration: +3,216 lb. in (363.359 N.m)
-3,209 lb. in (362.568 N.m)

2.2.2 Load and speed indicators: "Lebow" models 7540-154 and 7215-154

Torque conditioning unit:

excitation: regulated 5V, 3.28 kHz
non-linearity: ± 0.005% FS
temperature effect: 0.15% FS/100°F

Digital display:

resolution: 1 part in 10,000
accuracy: ± 1 count
linearity: ± 0.005% FS
stability: 0.15% FS/100°F

2.2.3 Servo controlled throttle actuator system: "Labeco" model 304. Angular position control and indication, adjustable for zero and WOT (wide open throttle) position of the carburettor shaft (indication 0 to 1,000)

2.2.4 Balance for mass fuel consuption measurement:

"Mettler" model PK 36

Range: 0 to 30,000 g

Resolution: 0.1 g in 0 to 6,000 g range ("Delta Range")
1.0 g in 6,000 to 30,000 g range

Calibration: self, 16,000 g

Repeatability: < 0.1 g in "Delta Range"
< 0.5 g

Linearity: ± 0.1 g in "Delta Range"
± 1.0 g

Temperature range: 0 to 40°C

2.2.5 Temperature measurement: "Doric Trendicator" model 400 A with 20 channels switching boxes and "Omega" thermocouples

thermocouple designation: K (Chromel-Alumel)

Range: - 200 to 1,250 °C

Accuracy of thermocouple: (ANSI MC 96.1-1975)
± 2.2°C or 0.75% whichever is greater (in range 0 to 1250°C)

Accuracy of indicator: ± 0.5°C

Junction: grounded

2.2.6 Pressure measurement: "Doric Trendicator" model 400 A with 5 channels voltmeter and "Viatran" strain-gauge pressure tranducers (amplifier included, 5V DC FS output)

Transducer error band: ± 0.4% FS

Temperature effect: ± 2% FS/100°F

Internal calibration accuracy: ± 1% FS

Frequency response: 7 Hz (model 223, 0-20 in H_2O)
2 kHz (model 218)

2.2.7 Hydrocarbon analyzer: "Beckman" model 400

Measuring method: flame ionization detector (FID)

Ranges (as calibrated): 0-10, 0-25, 0-100, 0-250, 0-1,000, 0-2,500 and 0-10,000 parts per million (ppm) CH_4 equivalent

Reproductibility: 1% FS

Response speed: 90% within 0.5 s

2.2.8 NO Analyzer: "Beckman" model 951

Measuring method: chemiluminiscence

Ranges: 0-10, 0-25, 0-100, 0-250, 0-1,000, 0-2,500 and 0-10,000 ppm

Sensitivity: 0.1 ppm on 10 ppm range

Linearity: ± 1% FS

Precision: 0.5% FS

Dynamic response: ≤ 1s

2.2.10 O_2 Analyzer: "Beckman" model OM-11

Measuring method: polarographic

Range: 0-25%

Accuracy: ± 1% FS

Linearity: ± 1.2% O_2

Response Speed: 90% within 300 to 600 ms

2.2.11 CO and CO_2 Analyzers: "Beckman" model 864

Measuring method: non-dispersive infrared (NDIR)

Ranges: 0-2 and 0-10% CO
0-20% CO_2

Precision: 1% FS

Noise: 1% FS

Zero or Span Drift: ± 1% FS for 24 h

Response Speed: adjustable, 90% in 0.5 to 26 s

2.2.12 Exhaust sample conditioning system: "Beckman", with diaphragm compressor and air dryer

2.2.13 Ignition timing: "Beckman" model IST 1560 ignition system tester

Range: 0-45° advance or retard

2.2.14 Barometric pressure: "Eberbach" mercury barometer, 0.01 in divisions

2.2.15 Water vapour pressure in atmosphere: "Johnson" sling-psychrometer

3. TEST PROCEDURE

The test procedure is based on the SAE Standard J 816 b - "Engine Test Code - Spark Ingition and Diesel" and "GM Engine Test Code" - VI edition, test 1 - "Full throttle, as installed".

During the test, the **net power** as defined by the SAE Standard is measured, i.e. the engine is equipped with all the built-in accessories (fuel, oil and coolant pumps) and all the accessories necessary to perform its intended functions unaided (intake, exhaust, cooling, electric and emissions control systems). Specifically, this includes:

- air cleaner
- fan
- all standard emissions controls
- muffler
- alternator (belt driven, without load)

The parameters measured during the test are:

- engine rotational speed, N [rpm]
- torque, T [N.m]
- mass fuel consumption, W [g]
- inlet air temperature at filter [°C]
- inlet manifold air-fuel charge temperature [°C]
- average exhaust gas temperature [°C]
- exhaust gas temperature in the port of each cylinder [°C]
- spark advance BTDC [°]

- manifold vacuum [kPa]
- outlet cooling water temperature [°C]
- lubrication oil pressure at filter [kPa]
- relative throttle position
- barometric pressure, B [kPa]
- ambient temperature, t [°C]
- wet and dry bulb temperatures [°F] for water vapour pressure in atmosphere, e [kPa]
- HC (methane-CH_4-equivalent) emission [ppm]
- NO emission [ppm]
- O_2 emission [%]
- CO emission [%]
- CO_2 emission [%]

The following parameters are calculated for correction of data at standard ambient conditions:

- brake power, observed (at test conditions), bp_t [kW]
- brake mean effective pressure, observed, $bmep_t$ [kPa]
- mechanical efficiency, n[%]
- friction power, observed, fp [kW]
- mass fuel consumption per hour, observed, F_t [g/h]
- brake specific fuel consumption, observed, $bsfc_t$ [g/kW.h]
- barometric pressure, corrected for dry air conditions, B_d [kPa]
- correction factor for standard atmospheric conditions, C_s
- brake power, corrected bp_c [kW]
- torque, corrected T_c [N.m]

- brake mean effective pressure, corrected, $bmep_c$ [kPa]

The calculations are detailed in Appendix 1.

The air-fuel ratio (A/F) is calculated from the emission components (HC, NO, O_2, CO, CO_2). The theoretical background of the method is presented in Appendix 2. The various systems operations during the test are listed below:

a) stabilize thermal regime of the engine.

b) measure and record atmospheric conditions.

c) load the engine at WOT (wide open throttle) to obtain the minimum stabilized speed and record the listed parameters for a 2 minute period.

d) decrease the load at the same speed at 2/3, 1/3 and minimum obtainable from maxium load and record the listed parameters for a 2 minute period.

e) repeat steps c and d each 600 rpm, up to 3600 rpm, to cover the peak obtainable power for the test engine.

f) repeat all the steps a to e to check for consistency of data.

The baseline test with gasoline was conducted with the following settings:

- static timing 6° BTDC at max. 800 rpm (instruction on the emissions sticker of the engine)
- 88± 6°C (190± 10°F) thermostatic control of cooling water outlet from engine (SAE for dynamometer testing)
- all emissions controls in place and operational

The evaluation tests with propane were conducted at the settings listed below, recommended by the majority of propane carburetion systems suppliers:

- 71± 6°C (160± 10°F) thermostatic control of cooling

water outlet from engine

- carburettor base heat cross-over isolated
- all emission controls dismantled
- distributor static timing 6°BTDC and recalibrated by changing the springs and the vacuum advance unit to obtain the following values (IMPCO, BEAM, A.F.S.):

Speed [rpm]		1,200	1,800	2,400
advance [°]	gasoline	1	10	13
	propane	6	17	24
vacuum [in Hg]		4	8	
advance [°]	gasoline	2	8	
	propane	2	12	

- lay-out of installation for IMPCO, that is more elaborate, is presented in Figure 3-1.
- for OXIN the static timing was set by manufacturer at 14° BTDC and the distributor mechanism was modified to obtain an increase from 14 to 30° between 1200 and 2400 rpm. According to manufacturer procedure, this system is not using the vacuum advance.

The design of IMPCO, BEAM and A.F.S. is the same as in the first two stages of this Project, where they were described. For the OXIN system no documentation is available from manufacturer.

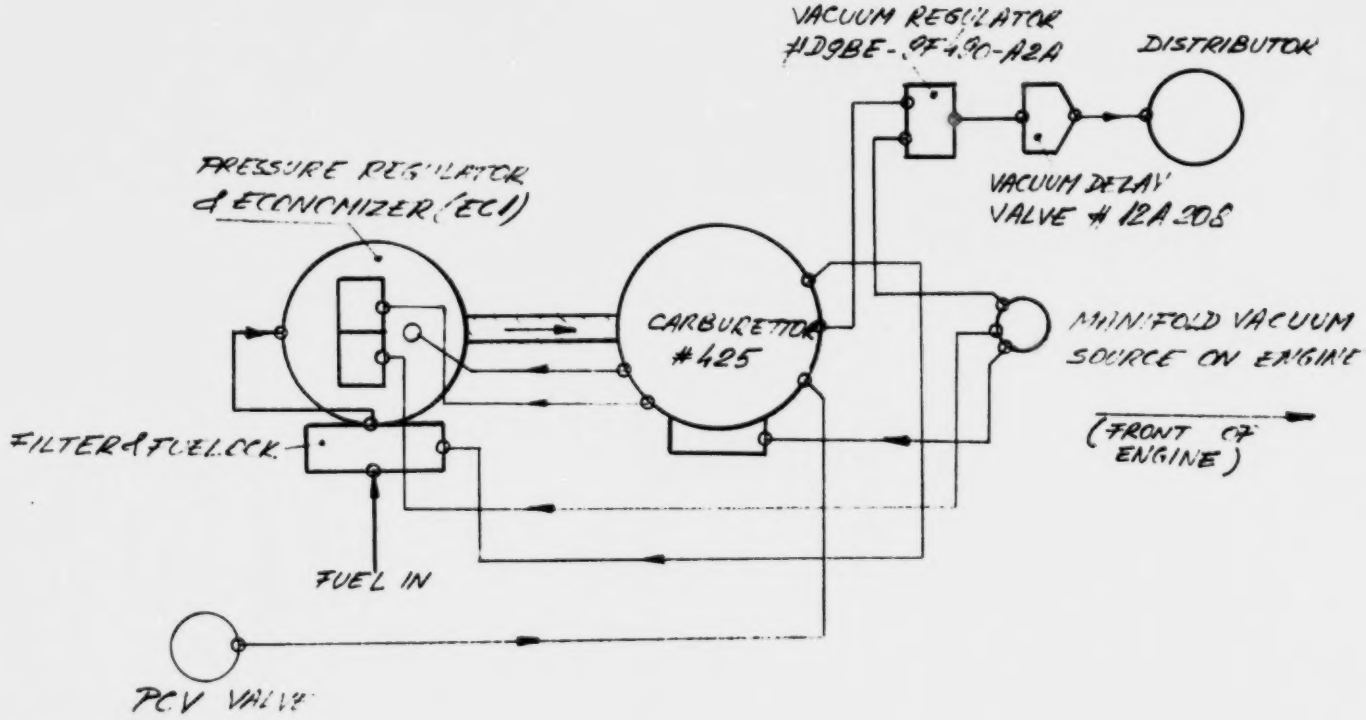


Figure 3-1: Lay-out of IMPCO propane carburetion system.

4. TESTS RESULTS AND INTERPRETATION

4.1 Preliminary

In this chapter test results are presented in their final form. That is, all data have been corrected to standard atmospheric conditions, averaged for all tests and compared with the gasoline baseline. The complete sets of raw data are available upon request. All data values represent the average of at least two runs; up to four when the spread of data required.

4.2 Corrected Brake Power

In the Table 4-1 and Figure 4-1 is presented corrected brake power at wide open throttle (WOT). For ease of comparison, the percentage difference between propane and gasoline carburetion systems is also presented. For the best systems tested, the power developed using propane is generally 0.9 to 3.7% lower than for gasoline. Larger reductions in power output (up to 23.3%), encountered for the systems tested, are due to larger differences between the timing and air-fuel ratio at which those systems are operating and the optimum values for those two basic parameters.

The correlation between the air-fuel ratio established by the carburetion systems design and the power developed is presented in Figure 4-2. A 0.1 difference in equivalence A/F ratio is translated in about 10% difference in power.

In Table 4-2 and Figure 4-3 are the results of inlet charge temperature measurements, with a lower and more stable temperature for propane at partial loads. This condition is favourable for an improved thermal efficiency of the engine using propane.

4.3 Measured Brake Specific Fuel Consumption

The mass base fuel consumption is presented in Tables 4-3 to 4-6 and Figure 4-4. The propane has generally an improved economy , consumption dropping by 11.2 to 33.2%, depending on load and speed, for the best systems.

A more direct comparison of efficiencies between propane and gasoline is given in Tables 4-7 to 4-10 and Figure 4-5, on the common base of energy content. The energy efficiency of the best propane carburetion systems increases by 6.4 to 29.6%, a significant advantage in favour of this fuel versus gasoline. In Table 4-11 are concentrated the results of those improvements in energy efficiency, offering an overall 10.8 to 21.0% increase for the best systems tested. The correlation between the specific fuel consumption (in energy units) and the equivalence air-fuel ratio at which different carburetion systems are running is described in Figures 4-6 to 4-8.

For a comparison of fuel prices as sold in volumetric units, the results are translated into a volume base in Tables 4-12 to 4-15. Due to the difference in density, the

volumetric consumption with propane is generally higher (ranging up from a low of 14.2% to 28.9% for the best systems). The maximum increase can reach 54.8% if the carburetion system is set too far from the optimum.

4.4 Distributor Vacuum

The values of distributor vacuum are indicated in Table 4-16 and Figure 4-9. As for the previously tested engines, the loads fix the vacuum values in clearly defined groups,

load.

4.5 Total Spark Advance

The total advance is presented in Table 4-17 and Figure 4-10.

4.6 Relative Throttle Position

The relative throttle position is shown in Table 4-18.

4.7 Exhaust Gas Temperature

4.7.1 Average Downstream Temperature

In Table 4-19 and Figure 4-11 the average exhaust temperatures are recorded. The values are very close for the two fuels. The correlation between exhaust temperature and air-fuel ratio is presented in Figures 4-12 and 4-13.

4.7.2 Cylinder Temperature

The distribution of exhaust gas temperatures among cylinders, as a translation of the air-fuel ratio distribution, is recorded in Tables 4-20 to 4-22 and in Figures 4-14 to 4-16. A poor distribution of mixture to cylinders 2 and 7 has to be mentioned, expecially for gasoline. A more uniform temperature for propane can be observed.

4.8 Hydrocarbons Emission

The results for HC emission are presented in Table 4-23 and Figure 4-17. The values are lower for propane (40.6 to 99.2% for the best systems), if compared with the gasoline system without the air-pump emission control device. For a fully emission equipped gasoline system, the values are in the favour of gasoline or propane carburettors, depending on load and speed. Use of emission control devices can be beneficial for propane systems too, with the corresponding power penalty.

4.9 Nitric Oxide Emission

The results for NO emission are given in Table 4-24 and Figure 4-18. The values for propane vary between 74.4% lower and 578.6% higher than for gasoline, in the conditions of this test-gasoline with all emission controls active, propane without emission controls. Expecially damaging is the region of equivalence air-fuel ratio 1.02 ÷ 1.06, where the increases are maximal. Once again, the use of emission control devices can be beneficial, in particular the use of EGR (exhaust gas recirculation) valve.

4.10 Excess Oxygen

The results for O_2 emission are recorded in Table 4-25 and Figure 4-19. The level of the excess oxygen is generally higher for the propane systems, as a result of leaner air-fuel mixtures.

4.11 Carbon Monoxide Emission

The results for CO emission are given in Table 4-26 and Figure 4-20. The level of this emission is generally lower for propane, reaching in one point only 1.9% of the value for gasoline with the air pump disconected. The levels are comparable if all gasoline emission controls are active, except the WOT (wide open throttle) loads, where the propane has still an advantage.

4.12 Carbon Dioxide Emission

CO_2 emission is presented in Table 4-27. The maximum for this emission is in the stoichiometric region.

To obtain correct calculation of air-fuel ratio for gasoline, the values of emissions for this system are presented with the air pump inactive. In Table 4-28, the values of all emissions for gasoline with the air pump active are recorded. The correspondent points are figured in all emission graphs too. This represents a vehicle set up to pass the emission standards.

4.13 Air-Fuel Ratio

The air-fuel ratio, calculated from the emission values, is presented in Tables 4-29 and 4-30 and in Figure 4-21. The effect of the design of the gasoline carburettor, with air-fuel ratio 0.88 to 0.90 at WOT and around 1.00 for partial loads, can be observed. By comparison the economy of the propane system, running leaner, is enhanced.

Table 4-1: Performance (Maximum power at WOT)

$\frac{\text{[kW]}}{\text{\% vs. gasoline}}$, average values

Carburetion system	Engine speed [rpm]				
	1200	1800	2400	3000	3600
Gasoline	43.55	67.30	95.72	117.93	116.70
IMPCO	33.38	62.99	92.14	114.95	125.45
	-23.35	-6.40	-3.74	-2.53	+7.50
BEAM	38.88	61.51	87.61	105.58	112.36
	-10.72	-8.60	-8.47	-10.47	-3.72
A.F.S.	38.60	61.79	88.47	107.29	112.53
	-11.37	-8.19	-7.57	-9.02	-3.57
OXIN	43.17	65.77	89.22	104.62	108.77
	-0.87	-2.27	-6.79	-11.29	-6.80

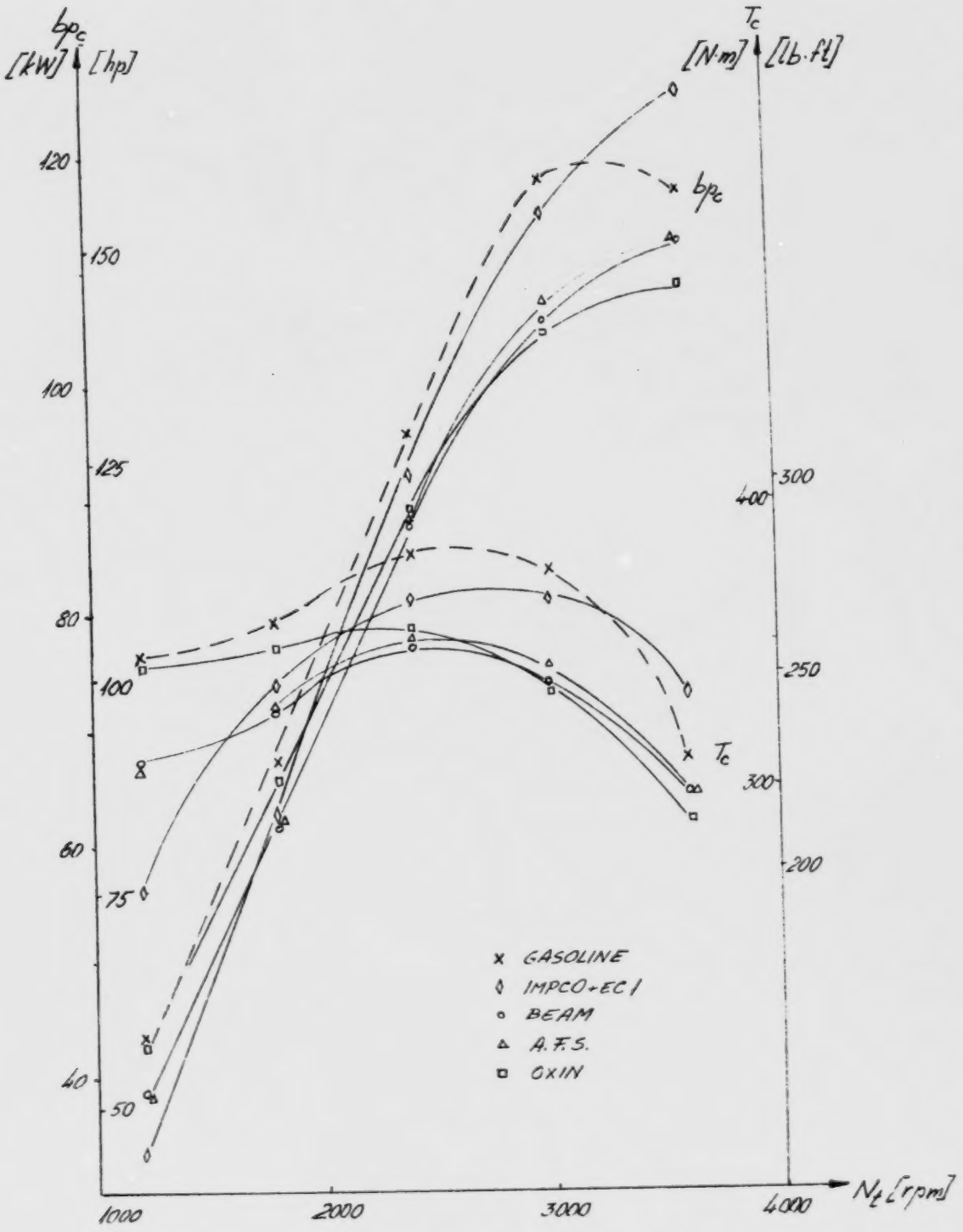


Figure 4-1: Comparison of corrected brake power at wide open throttle.

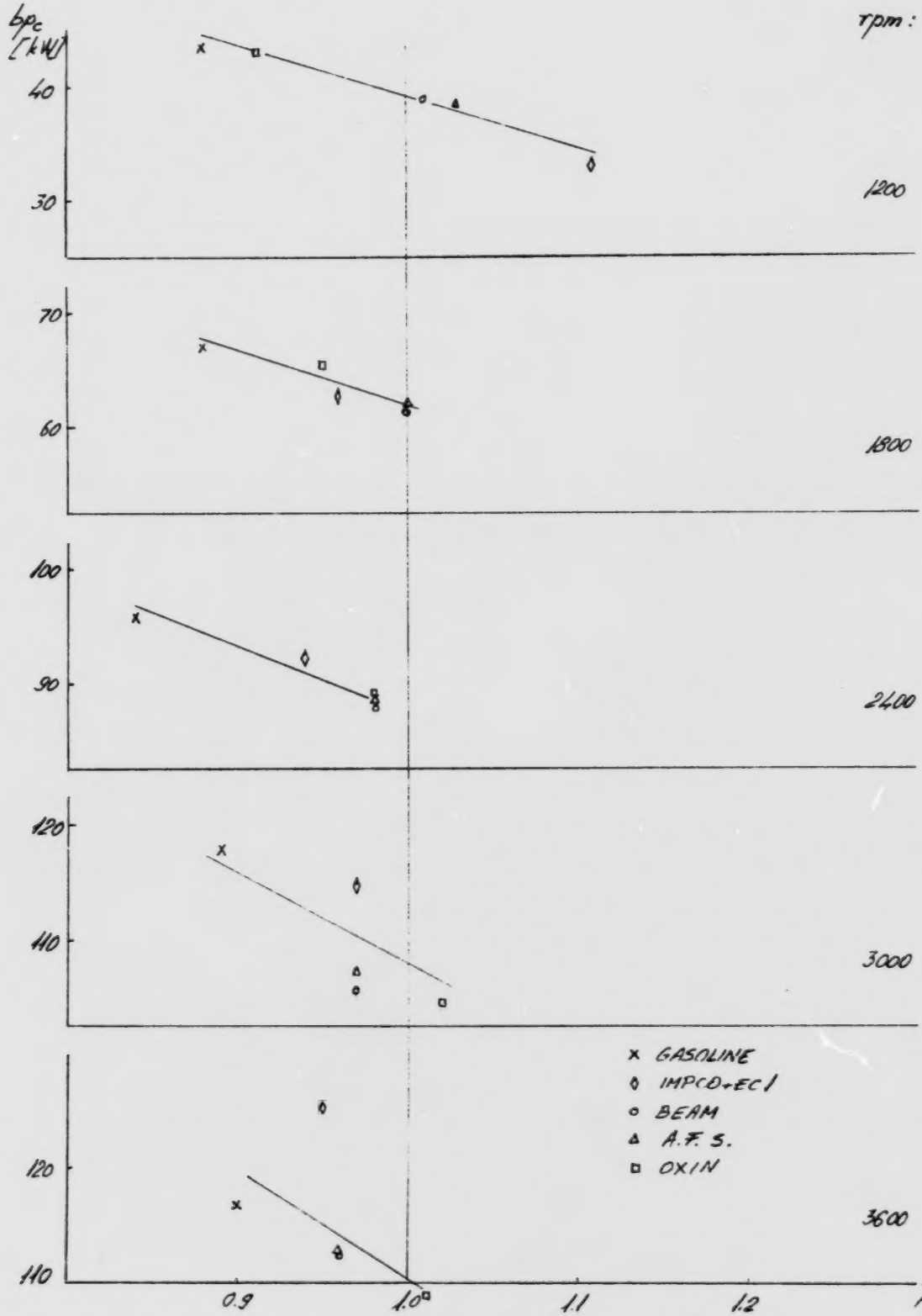


Figure 4-2: Correlation between WOT power and air-fuel ratio.

Table 4-2: Inlet Manifold Air-Fuel Charge Temperature [°C], average values

Load [%]	Carburetion System	Engine Speed [rpm]				
		1200	1800	2600	3000	3600
100	Gasoline	34	33	32	33	33
	IMPCO	34	35	35	36	38
	BEAM	35	36	35	35	37
	A.F.S.	31	32	34	36	36
	OXIN	32	35	37	37	37
66	Gasoline	42	58	69	64	60
	IMPCO	40	40	39	40	39
	BEAM	39	41	38	38	39
	A.F.S.	38	38	39	39	40
	OXIN	38	41	41	40	40
33	Gasoline	45	48	75	78	77
	IMPCO	41	43	41	42	42
	BEAM	40	43	40	39	41
	A.F.S.	39	40	41	41	41
	OXIN	40	43	43	42	42

	Gasoline	46	48	51	62	74
	IMPCO	45	45	43	45	44
~0	BEAM	42	45	43	43	43
	A.F.S.	40	42	44	43	44
	OXIN	43	44	45	44	44

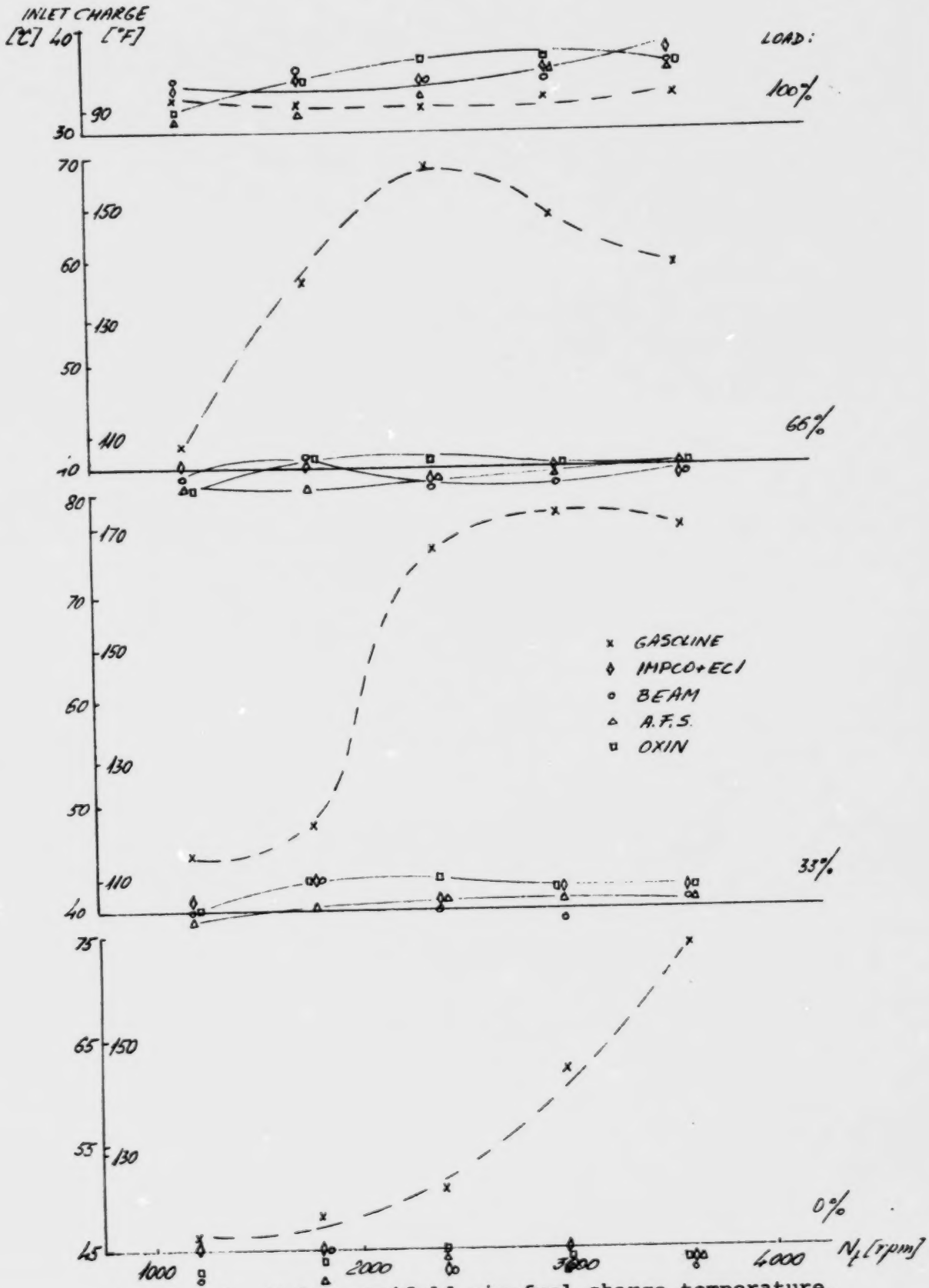


Figure 4-3: Inlet manifold air-fuel charge temperature.

Table 4-3: Brake Specific Fuel Consumption

Mass Base - 100% Load

$\frac{\text{[g/kW.h]}}{\text{\% vs. gasoline}}$, average values

Carburetion system	Engine speed [rpm]				
	1200	1800	2400	3000	3600
Gasoline	366.40	354.53	337.77	328.81	353.84
IMPCO	323.33	287.58	278.41	279.89	299.12
	-11.75	-18.88	-17.57	-14.88	-15.46
BEAM	306.82	281.32	272.90	289.41	307.35
	-16.26	-20.65	-19.21	-11.98	-13.14
A.F.S.	301.93	282.97	273.99	284.45	303.13
	-17.60	-20.18	-18.88	-13.49	-14.33
OXIN	297.50	278.40	271.68	285.90	317.90
	-18.80	-21.47	-19.57	-13.05	-10.16

Table 4-4: Brake Specific Fuel Consumption

Mass Base - 66% Load

$\frac{[g/kW.h]}{\%\ vs.\ gasoline}$, average values

Carburetion system	Engine speed [rpm]				
	1200	1800	2400	3000	3600
Gasoline	332.05	361.40	341.19	357.73	374.00
IMPCO	339.07	309.39	289.43	306.92	332.05
	+ 2.11	-14.39	-15.17	-14.20	-11.22
BEAM	289.39	286.13	281.46	306.14	340.86
	-12.85	-20.83	-17.51	-14.42	- 8.86
A.F.S.	296.15	288.12	290.64	309.60	351.86
	-10.81	-20.28	-14.82	-13.45	- 5.92
OXIN	306.94	301.30	293.10	317.34	354.46
	- 7.56	-16.63	-14.09	-11.29	- 5.22

Table 4-5: Brake Specific Fuel Consumption

Mass Base - 33% Load

$\frac{\text{[g/kW.h]}}{\text{\% vs. gasoline}}$, average values

Carburetion system	Engine speed [rpm]				
	1200	1800	2400	3000	3600
Gasoline	440.46	456.35	465.84	492.72	541.31
IMPCO	468.20	413.46	393.62	387.06	449.75
	+6.29	-9.40	-15.50	-21.44	-16.91
BEAM	393.88	376.94	367.50	402.12	467.17
	-10.58	-17.40	-21.11	-18.39	-13.70
A.F.S.	386.41	380.23	384.89	411.36	468.89
	-12.27	-16.68	-17.38	-16.51	-13.38
OXIN	407.38	403.42	394.52	434.52	508.30
	- 7.51	-11.60	-15.31	-11.81	- 6.10

Table 4-6: Brake Fuel Consumption

Mass Base - ~0% Load

$\frac{[g/h]}{\%\ vs.\ gasoline}$, average values

Carburetion system	Engine speed [rpm]				
	1200	1800	2400	3000	3600
Gasoline	3,842	5,764	7,769	10,329	13,220
IMPCO	3,300	4,413	6,795	8,250	10,335
	-14.11	-23.44	-12.54	-20.13	-21.82
BEAM	2,940	3,852	6,300	7,455	10,335
	-23.48	-33.17	-18.91	-27.82	-21.82
A.F.S.	3,285	4,493	6,333	8,085	10,500
	-14.50	-22.05	-18.48	-21.73	-20.57
OXIN	3,435	5,370	6,765	8,910	11,505
	-10.59	- 6.84	-12.92	-13.74	-12.97

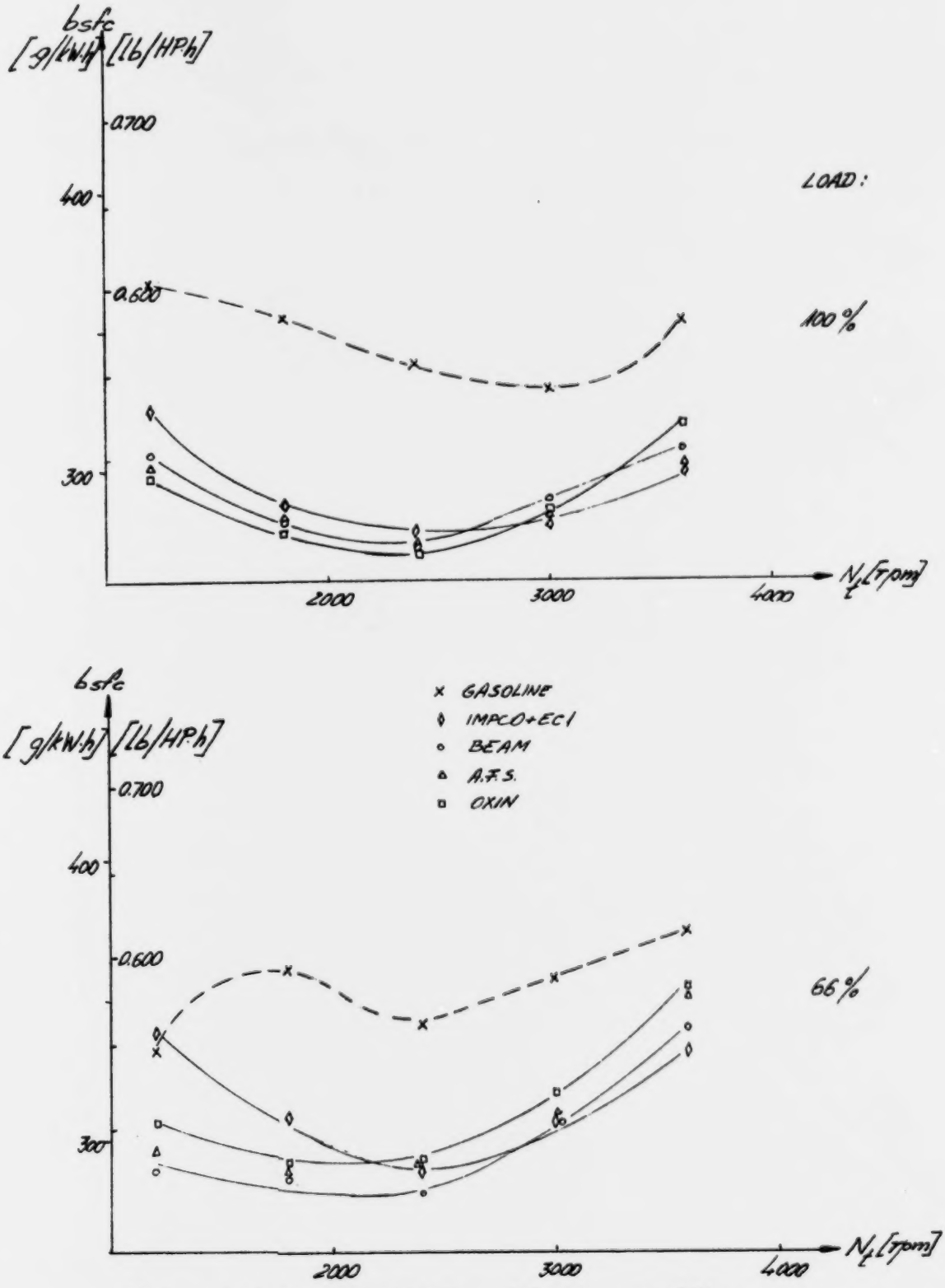


Figure 4-4.1: Comparison of brake specific fuel consumption - mass base.

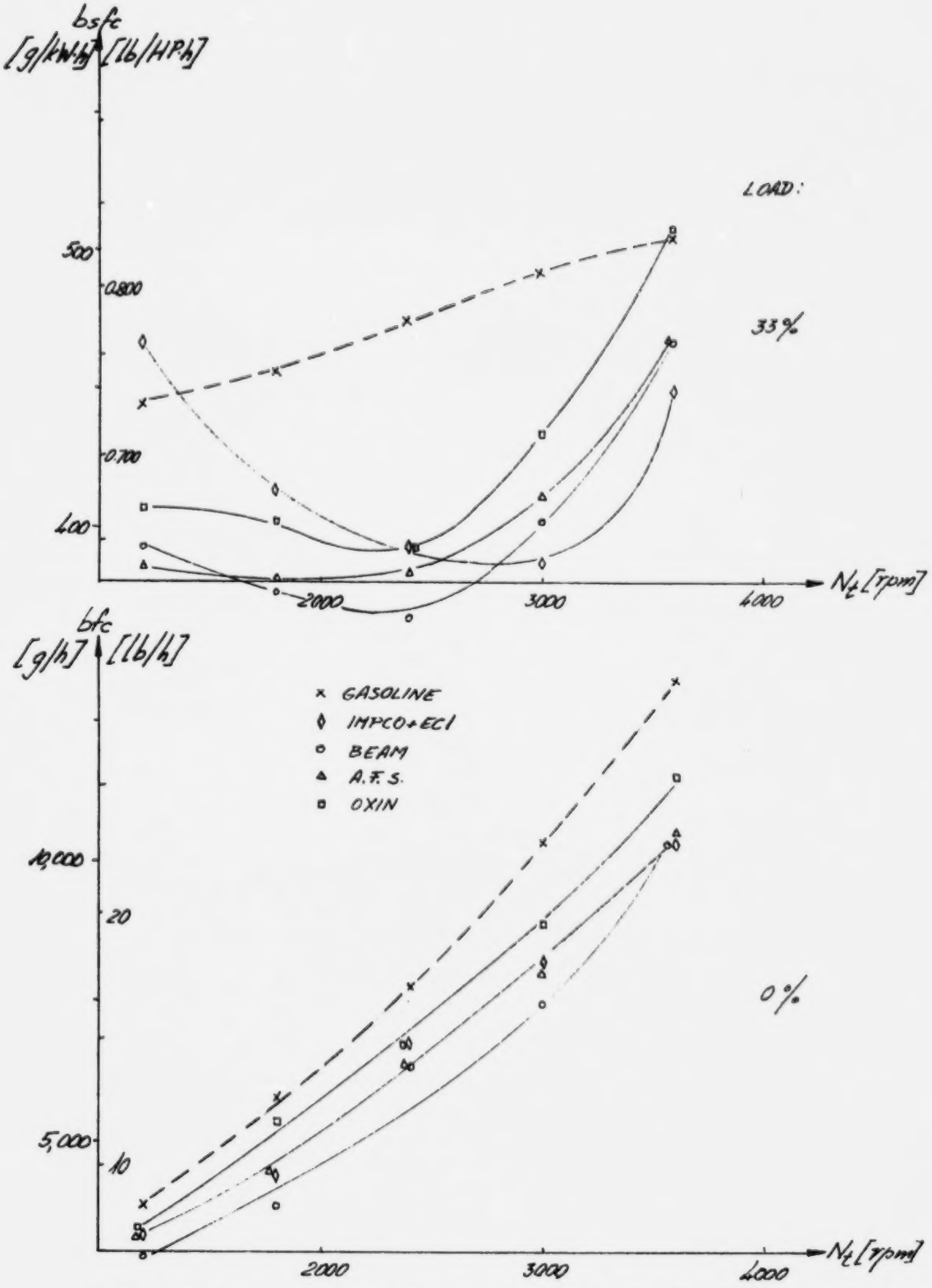


Figure 4-4.2: Comparison of brake specific fuel consumption - mass base/continuation.

Table 4-7: Brake Specific Fuel Consumption

Energy Base - 100% Load

[kJ/kW.h] , average values
% vs. gasoline

Carburetion system	Engine speed [rpm]				
	1200	1800	2400	3000	3600
Gasoline	16,123	15,600	14,863	14,469	15,570
IMPCO	14,996	13,338	12,913	12,982	13,873
	-6.99	-14.50	-13.12	-10.28	-10.90
BEAM	14,231	13,048	12,657	13,423	14,255
	-11.73	-16.35	-14.84	- 7.23	- 8.45
A.F.S.	14,004	13,124	12,708	13,193	14,059
	-13.14	-15.87	-14.50	- 8.82	- 9.70
OXIN	13,798	12,912	12,601	13,260	14,745
	-14.42	-17.23	-15.22	- 8.36	- 5.30

Net heat of combustion @ 25°C, constant p:
- gasoline: 44,003 kJ/kg
- propane: 46,381 kJ/kg

Table 4-8: Brake Specific Fuel Consumption

Energy Base - 66% Load

$\frac{\text{[kJ/kW.h]}}{\text{\% vs. gasoline}}$, average values

Carburetion system	Engine speed [rpm]				
	1200	1800	2400	3000	3600
Gasoline	14,611	15,903	15,013	15,741	16,457
IMPCO	15,726	14,350	13,424	14,235	15,401
	+7.63	-9.77	-10.58	-9.57	-6.42
BEAM	13,422	13,271	13,054	14,199	15,811
	- 8.14	-16.55	-13.05	- 9.80	- 3,93
A.F.S.	13,736	13,368	13,480	14,360	16,320
	- 5.99	-15.94	-10.21	- 8.77	- 0.83
OXIN	14,236	13,975	13,594	14,719	16,440
	- 2.57	-12.12	- 9.45	- 6.49	- 0.10

Table 4-9: Brake Specific Fuel Consumption

Energy Base - 33% Load

$\frac{\text{[kJ/kW.h]}}{\text{\% vs. gasoline}}$, average values

Carburetion system	Engine speed [rpm]				
	1200	1800	2400	3000	3600
Gasoline	19,382	20,081	20,498	21,681	23,819
IMPCO	21,716	19,177	18,256	17,952	20,860
	+12.04	-4.50	-10.94	-17.20	-12.42
BEAM	18,269	17,483	17,045	18,651	21,668
	- 5.74	-12.94	-16.85	-13.98	- 9.03
A.F.S.	17,922	17,635	17,852	19,079	21,748
	- 7.53	-12.18	-12.91	-12.00	- 8.69
OXIN	18,895	18,711	18,298	20,153	23,575
	- 2.51	- 6.82	-10.73	- 7.05	- 1.02

Table 4-10: Brake Fuel Consumption

Energy Base - ~0% Load

$\frac{[kJ/h]}{\%\text{ vs. gasoline}}$, average values

Carburetion system	Engine speed [rpm]				
	1200	1800	2400	3000	3600
Gasoline	169,060	253,633	341,859	454,507	581,720
IMPCO	153,057	204,679	315,159	382,643	479,348
	-9.47	-19.30	-7.81	-15.81	-17.60
BEAM	136,360	178,660	292,200	345,770	479,348
	-19.34	-29.56	-14.53	-23.92	-17.60
A.F.S.	152,362	208,389	293,730	374,990	487,001
	- 9.88	-17.84	-14.08	-17.50	-16.28
OXIN	159,319	249,066	313,767	413,255	533,613
	- 5.76	- 1.80	- 8.22	- 9.08	- 8.27

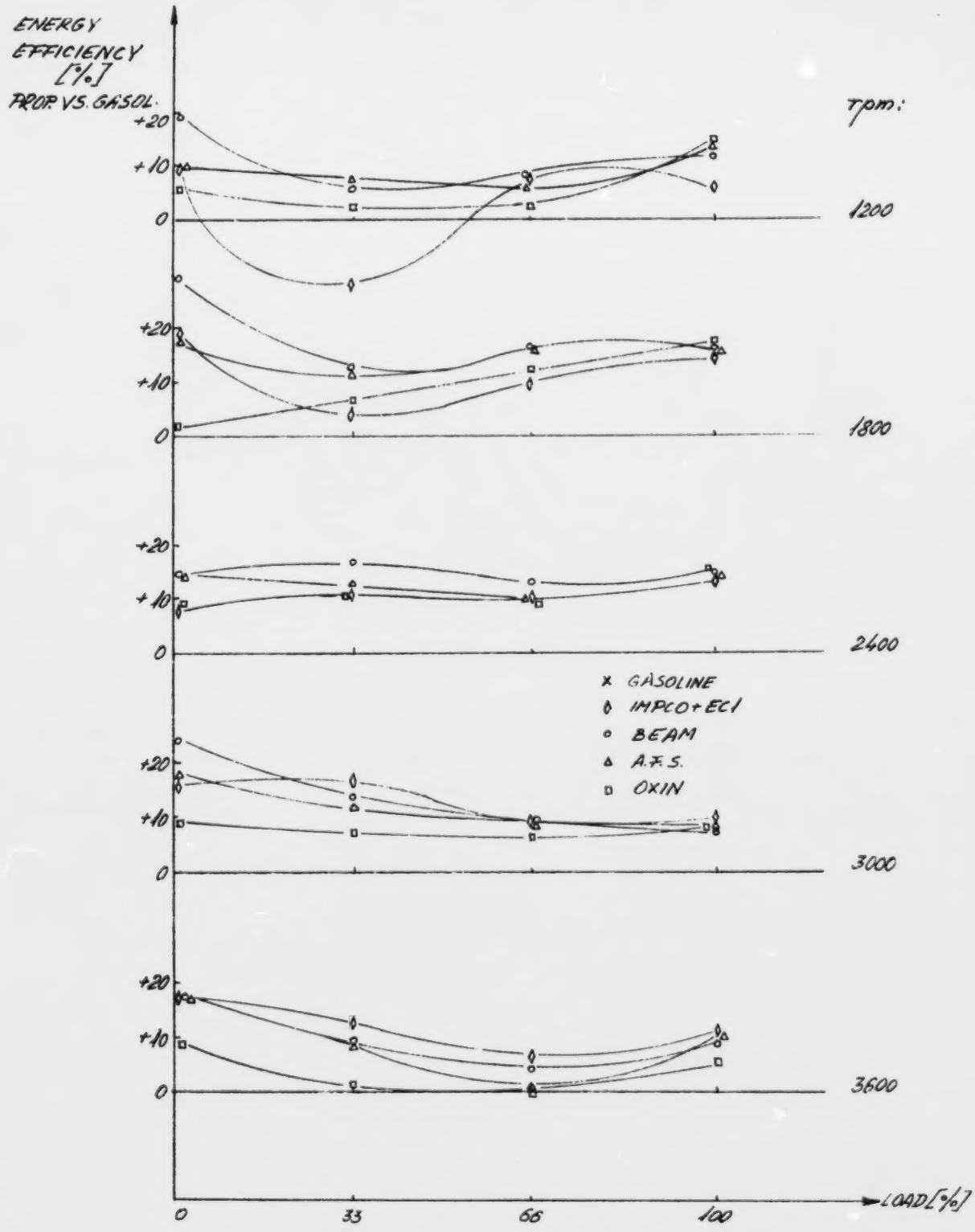


Figure 4-5: Energy efficiency of propane carburetion systems versus gasoline.

Table 4-11: Improvements in Energy Efficiency [%] for the Propane Carburetion Systems vs. Gasoline

LOAD [%]	CARBURETION SYSTEM	ENGINE SPEED [rpm] 1200	1800	2400	3000	3600	Average
		AVERAGE FOR 4 SYSTEMS					
100		+11.57	+15.99	+14.42	+ 8.67	+ 8.59	+11.85
66		+ 2.27	+ 13.60	+10.82	+ 8.66	+ 2.82	+ 7.63
33		+ 0.94	+ 9.11	+12.86	+12.56	+ 7.79	+ 8.65
0		+11.11	+17.13	+11.16	+16.58	+14.94	+14.18
		MAXIMUM FOR THE BEST SYSTEMS					
66	BEAM IMPCO + ECI	+ 8.14	+16.55	+13.05	+ 9.80	+ 6.42	+10.79
33	A.F.S. BEAM IMPCO & ECI	+ 7.53	+12.94	+16.85	+17.20	+12.42	+13.39
0	BEAM IMPCO & ECI	+19.34	+29.56	+14.53	+23.92	+17.60 +17.60	+20.99

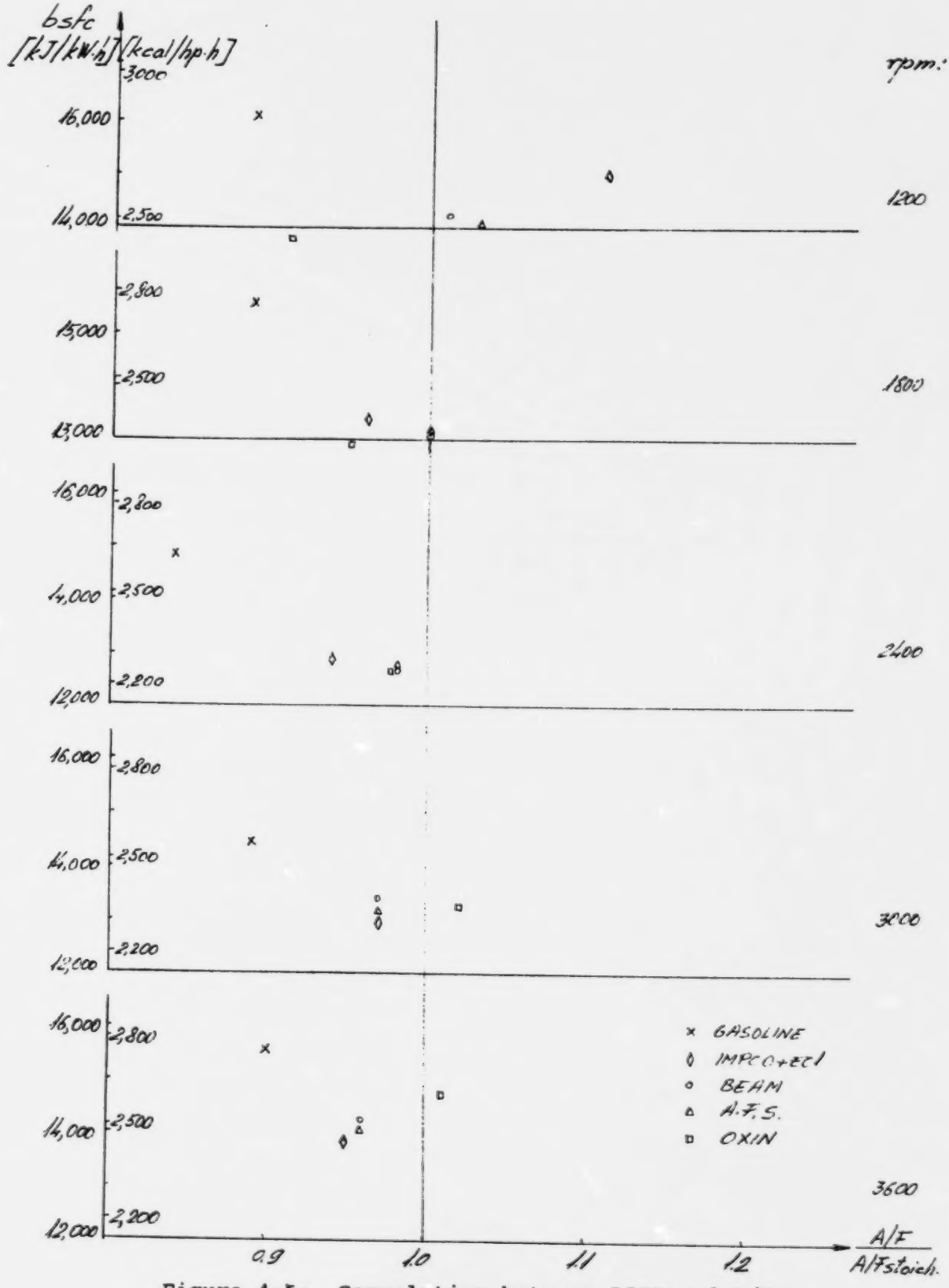


Figure 4-5: Correlation between BSFC and A/F ratio - 100% load.

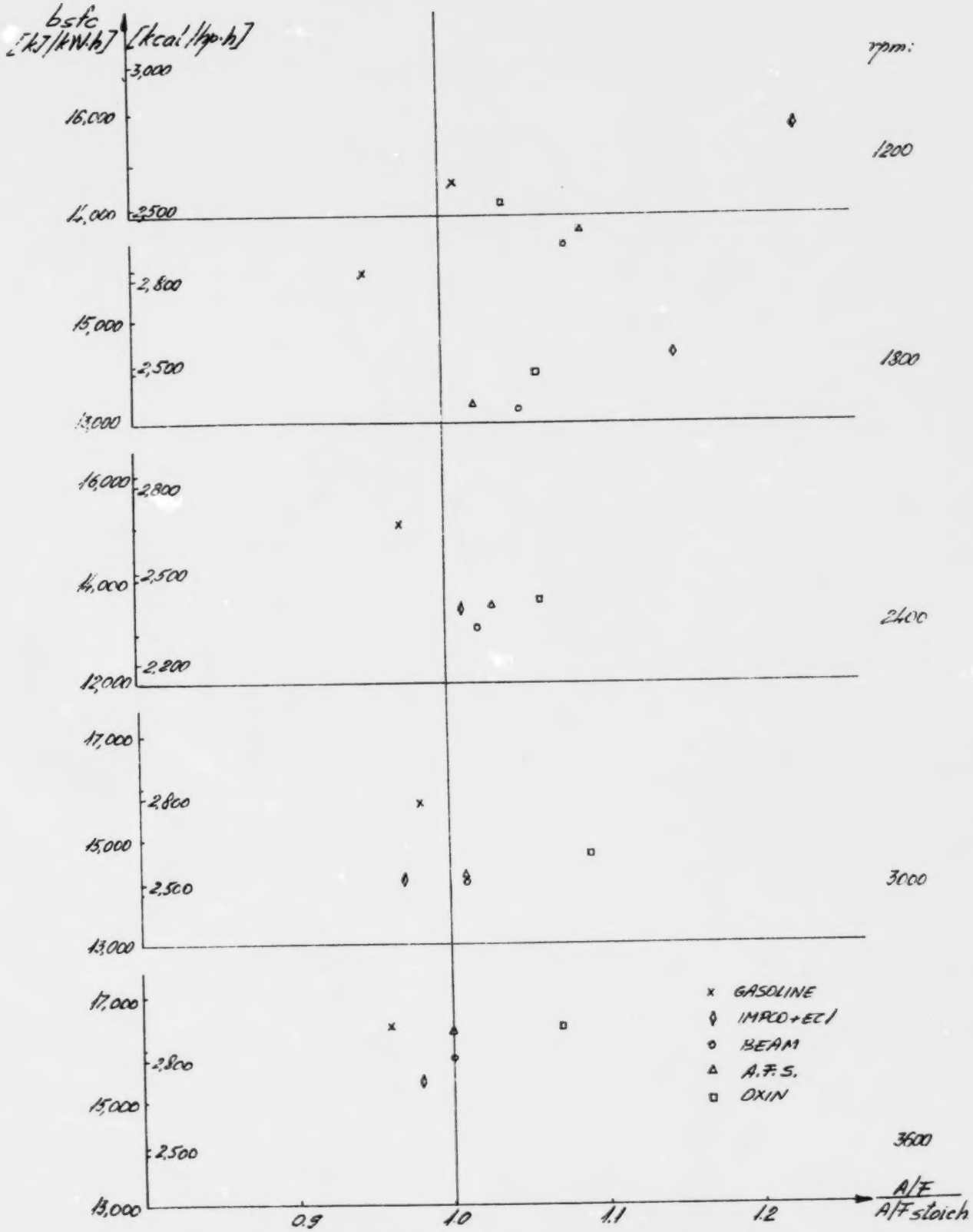


Figure 4-7: Correlation between BSFC and A/F ratio - 66% load.

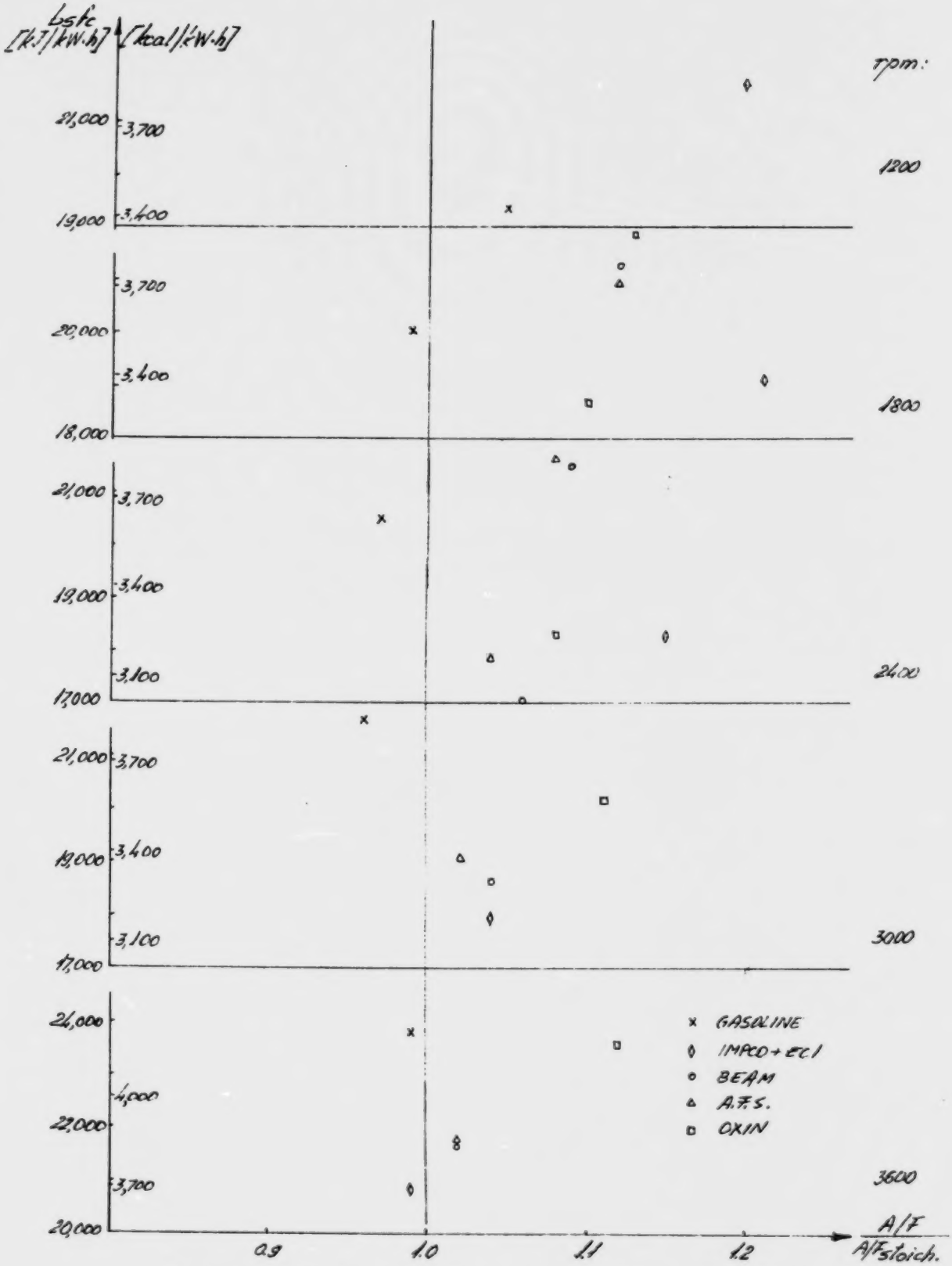


Figure 4-8: Correlation between BSFC and A/F ratio - 33% load.

Table 4-12: Brake Specific Fuel Consumption

Volume Base - 100% Load

[L/kW.h] / % vs. gasoline , average values

Carburetion system	Engine speed [rpm]				
	1200	1800	2400	3000	3600
Gasoline	0.497	0.481	0.458	0.446	0.480
IMPCO	0.638	0.567	0.549	0.552	0.590
	+28.37	+17.88	+19.87	+23.77	+22.92
BEAM	0.605	0.555	0.538	0.571	0.607
	+21.73	+15.38	+17.47	+28.03	+26.46
A.F.S.	0.596	0.558	0.541	0.561	0.598
	+19.92	+16.01	+18.12	+25.78	+24.58
OXIN	0.587	0.549	0.536	0.564	0.627
	+18.11	+14.14	+17.03	+26.46	+30.63

Density of liquid @ 16°C:
- Gasoline: 0.7370 kg/L (1.3569 L/kg)
- Propane: 0.5069 kg/L (1.9728 L/kg)

Table 4-13: Brake Specific Fuel Consumption

Volume Base - 66% Load

$\frac{\text{[L/kW.h]}}{\text{\% vs. gasoline}}$, average values

Carburetion system	Engine speed [rpm]				
	1200	1800	2400	3000	3600
Gasoline	0.451	0.490	0.463	0.485	0.508
IMPCO	0.669	0.610	0.571	0.606	0.655
	+48.34	+24.49	+23.33	+24.95	+28.94
BEAM	0.571	0.564	0.555	0.604	0.673
	+26.61	+15.10	+19.87	+24.54	+32.48
A.F.S.	0.584	0.568	0.573	0.611	0.694
	+29.49	+15.92	+23.76	+25.98	+36.61
OXIN	0.601	0.594	0.578	0.626	0.699
	+33.26	+21.22	+24.84	+29.07	+37.60

Table 4-14: Brake Specific Fuel Consumption

Volume Base - 33% Load

$\frac{\text{[L/kW.h]}}{\text{\% vs. gasoline}}$, average values

Carburetion system	Engine speed [rpm]				
	1200	1800	2400	3000	3600
Gasoline	0.597	0.619	0.632	0.669	0.735
IMPCO	0.924	0.815	0.777	0.764	0.887
	+54.77	+31.66	+22.94	+14.20	+20.68
BEAM	0.777	0.744	0.725	0.793	0.922
	+30.15	+20.19	+14.72	+18.54	+25.44
A.F.S.	0.762	0.750	0.759	0.812	0.925
	+27.64	+21.16	+20.09	+21.38	+25.85
OXIN	0.804	0.796	0.778	0.857	1.003
	+34.67	+28.59	+23.10	+28.10	+36.46

Table 4-15: Brake Fuel Consumption

Volume Base - ~0% Load

$\frac{[L/h]}{\%\ vs.\ gasoline}$, average values

Carburetion system	Engine speed [rpm]				
	1200	1800	2400	3000	3600
Gasoline	5.213	7.821	10.542	14.015	17.938
IMPCO	6.510	8.706	13.405	16.276	20.389
	+24.88	+11.32	+27.16	+16.13	+13.66
BEAM	5.800	7.599	12.429	14.707	20.389
	+11.26	-2.84	+17.90	+ 4.94	+13.66
A.F.S.	6.481	8.864	12.494	15.950	20.714
	+24.32	+13.34	+18.52	+13.81	+15.48
OXIN	6.777	10.594	13.346	17.578	22.697
	+30.00	+35.46	+26.60	+25.42	+26.53

Table 4-16: Manifold Vacuum [kPa]

average values

Load [%]	Carburetion System	Engine Speed [rpm] 1200	1800	2400	3000	3600
100	Gasoline	0.88	2.35	2.53	3.23	6.85
	IMPCO	2.38	3.00	3.46	3.67	3.41
	BEAM	0.81	1.86	3.56	5.44	6.91
	A.F.S.	1.00	1.82	3.20	5.00	7.00
	OXIN	3.40	3.51	3.75	4.15	4.75
66	Gasoline	29.19	16.61	14.84	13.05	21.64
	IMPCO	25.33	23.16	25.85	25.75	23.89
	BEAM	27.15	26.93	26.00	25.92	26.02
	A.F.S.	28.50	27.56	25.45	24.80	25.40
	OXIN	22.20	22.98	23.10	21.00	22.10
33	Gasoline	51.75	49.66	41.80	39.78	37.66
	IMPCO	47.87	42.70	44.15	45.29	45.50
	BEAM	47.55	47.08	47.75	46.00	45.50

	A.F.S.	48.20	47.34	46.75	46.05	45.45
	OXIN	41.00	43.07	44.45	41.55	39.00
	Gasoline	46.08	66.97	76.75	71.86	59.24
	IMPCO	68.76	65.14	64.31	63.18	61.83
~0	BEAM	65.50	65.93	67.00	66.00	63.00
	A.F.S.	63.50	64.61	65.45	65.00	63.00
	OXIN	60.50	63.20	64.50	62.10	59.20

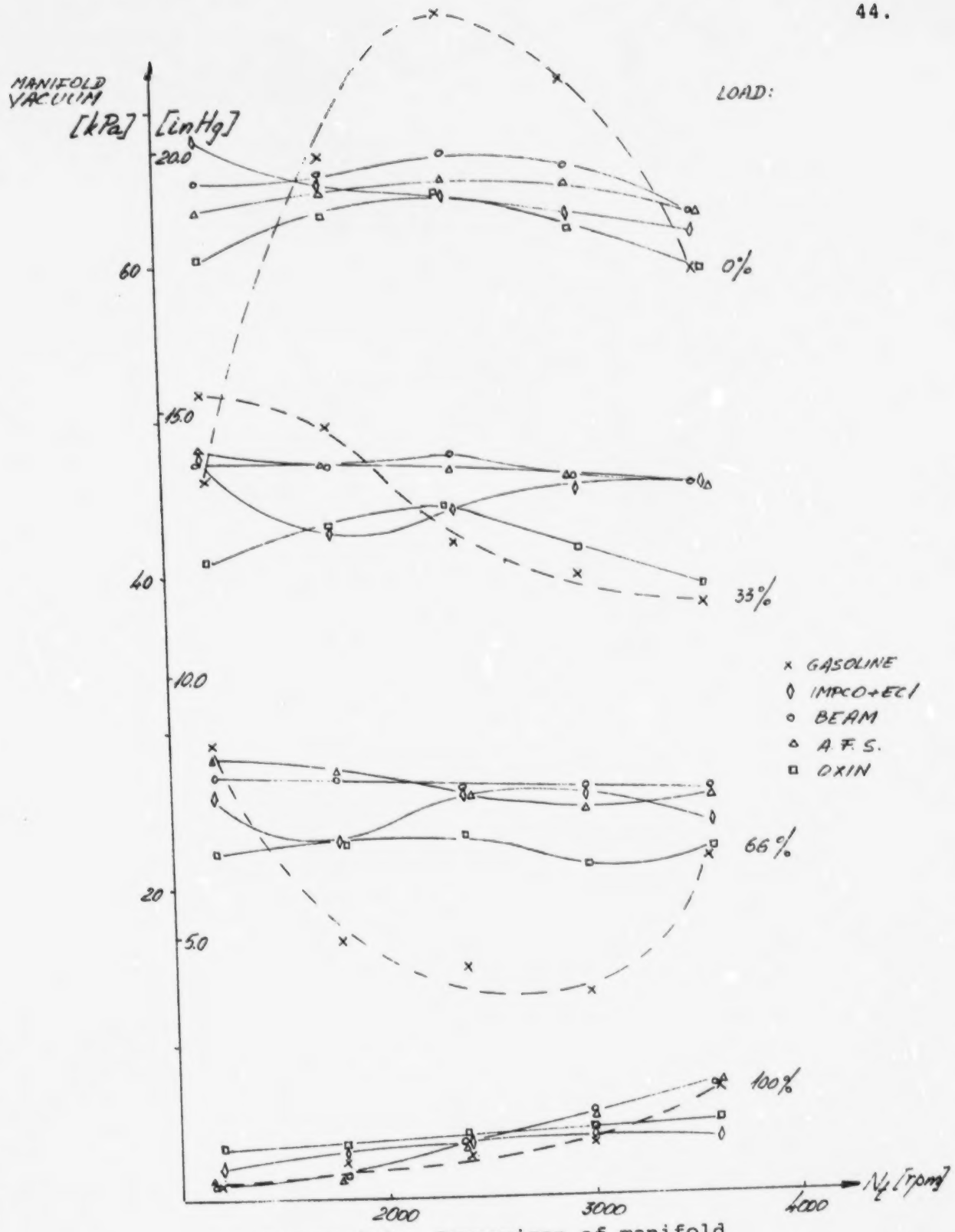


Figure 4-9: Comparison of manifold vacuum.

Table 4-17: Total Spark Advance [°]

average values

Load [%]	Carburetion System	Engine Speed [rpm] 1200	1800	2400	3000	3600
100	Gasoline	6.2	11.5	18.2	21.3	24.1
	IMPCO	6.9	16.4	24.5	32.5	33.8
	BEAM	7.0	15.3	24.5	31.8	33.5
	A.F.S.	6.5	15.4	25.0	32.5	33.5
	OXIN	14.3	20.9	30.5	30.0	28.00
66	Gasoline	14.3	16.3	23.5	24.5	32.0
	IMPCO	18.7	27.6	37.2	43.5	45.0
	BEAM	21.0	29.4	39.0	46.0	48.0
	A.F.S.	22.0	30.4	39.0	45.5	47.5
	OXIN	14.3	20.9	30.5	30.0	28.0
33	Gasoline	14.3	19.1	25.6	28.5	32.2
	IMPCO	22.8	33.0	40.9	47.8	49.8
	BEAM	22.8	31.2	40.9	48.3	50.0
	A.F.S.	22.3	30.9	40.3	47.8	50.0
	OXIN	14.3	20.9	30.5	30.0	28.0

	Gasoline	14.3	19.1	25.6	28.5	32.2
	IMPCO	22.9	33.3	41.0	48.3	50.0
~0	BEAM	22.3	31.4	40.9	48.3	50.0
	A.F.S.	22.3	30.9	40.3	48.3	50.0
	OXIN	14.3	20.9	30.5	30.0	28.0

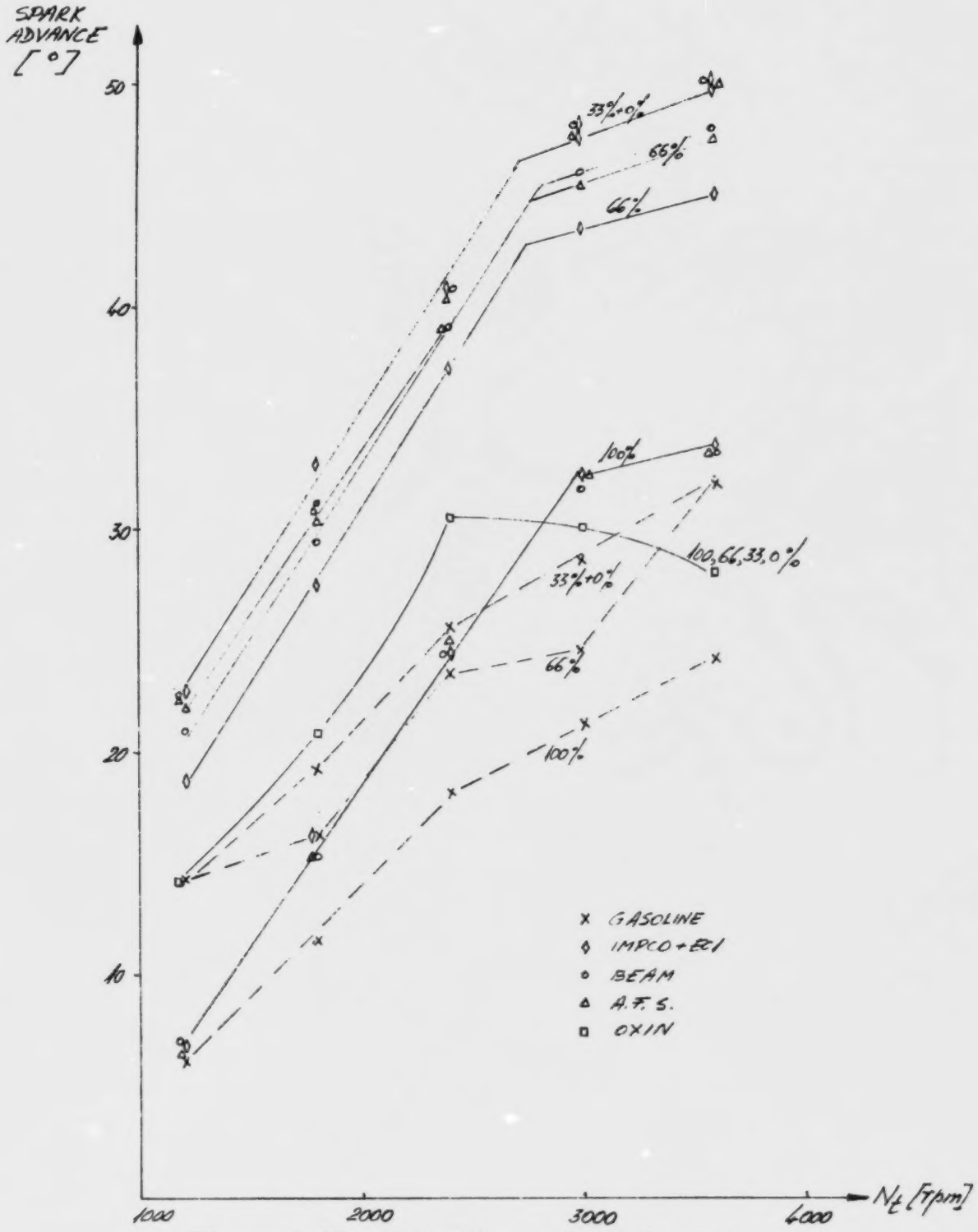


Figure 4-10: Comparison of total spark advance curves.

Table 4-18: Throttle Position (0 ÷ 1000 for idle ÷ WOT), average values

Load [%]	Carburetion System	Engine Speed [rpm] 1200	1800	2400	3000	3600
66	Gasoline	224	366	449	556	466
	IMPCO	278	348	374	419	445
	BEAM	204	276	346	379	413
	A.F.S.	272	335	405	464	499
	OXIN	246	296	340	389	407
33	Gasoline	148	209	268	325	347
	IMPCO	219	281	309	332	350
	BEAM	138	189	237	273	305
	A.F.S.	207	259	305	341	373
	OXIN	197	230	264	302	330
~0	Gasoline	97	130	164	199	240
	IMPCO	173	216	241	265	291
	BEAM	73	116	156	175	210
	A.F.S.	163	190	224	249	284
	OXIN	158	177	201	229	257

Table 4-19: Exhaust Gas Temperature [°C]
average values

Load [%]	Carburetion System	Engine Speed [rpm]				
		1200	1800	2400	3000	3600
100	Gasoline	425	541	604	678	719
	IMPCO	504	581	620	669	714
	BEAM	424	536	595	662	667
	A.F.S.	439	538	569	652	693
	OXIN	422	530	588	680	738
66	Gasoline	378	489	585	667	657
	IMPCO	392	489	553	623	638
	BEAM	397	529	553	620	675
	A.F.S.	396	501	571	629	670
	OXIN	424	524	583	658	719
33	Gasoline	340	415	513	588	635
	IMPCO	342	458	496	565	592
	BEAM	342	462	529	562	602
	A.F.S.	348	426	516	568	612
	OXIN	396	485	537	611	664

	Gasoline	288	356	417	503	538
	IMPCO	268	361	424	486	513
~0	BEAM	286	325	435	484	528
	A.F.S.	265	381	417	484	537
	OXIN	337	389	454	538	587

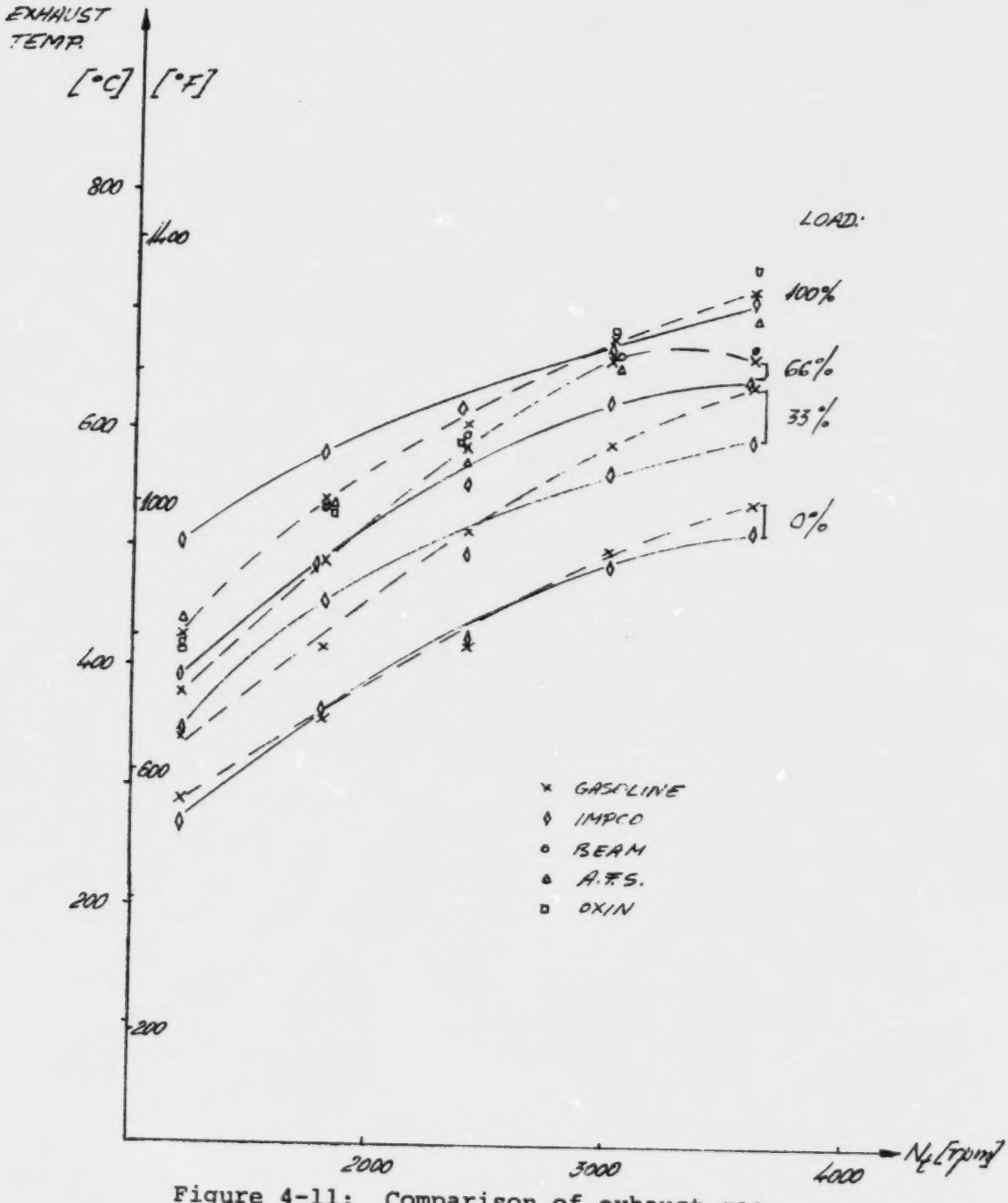


Figure 4-11: Comparison of exhaust gas temperature.

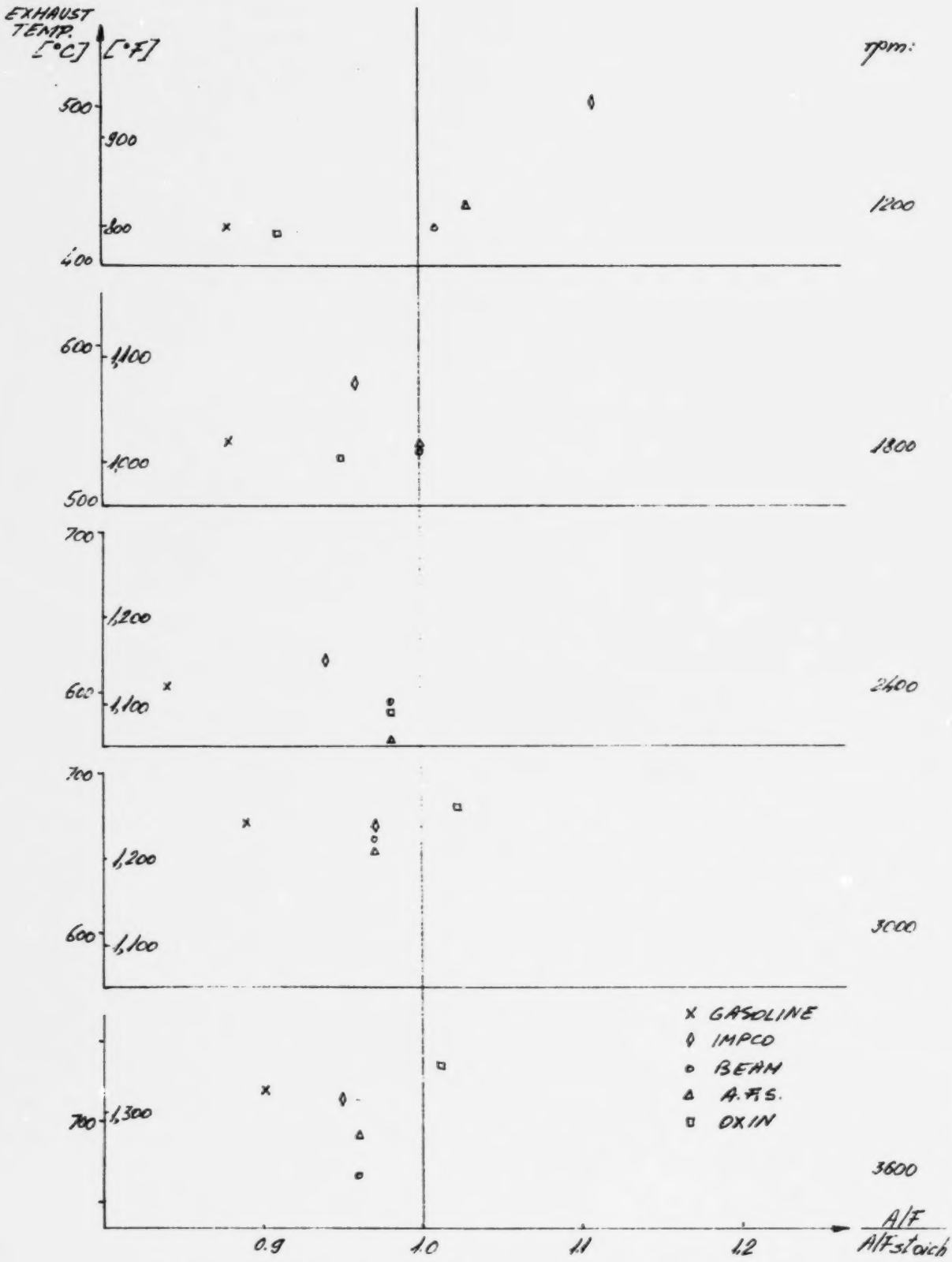


Figure 4-12: Correlation between exhaust gas temperature and A/F ratio - 100% load.

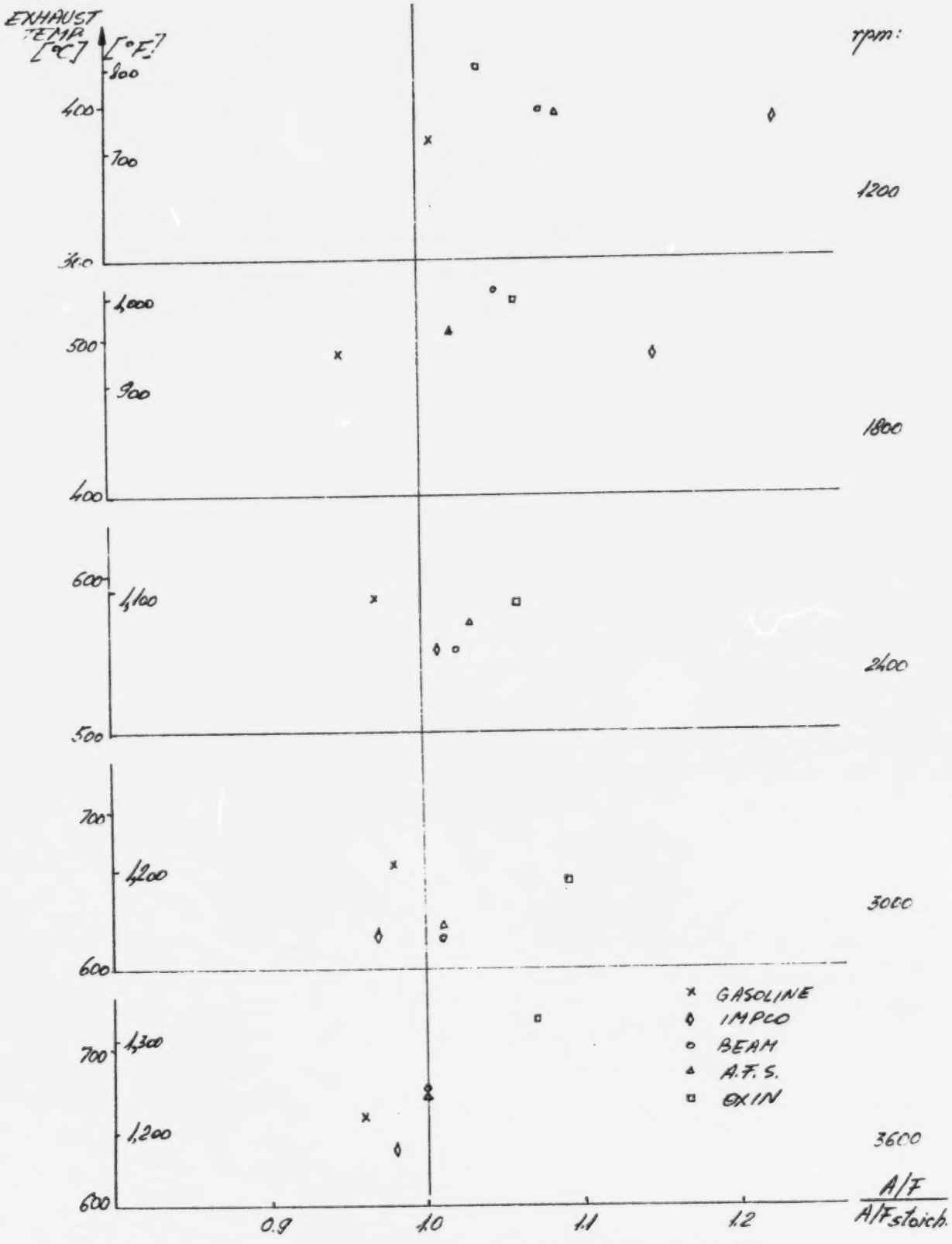


Figure 4-13: Correlation between exhaust gas temperature and A/F ratio - 66% load.

Table 4-20: Distribution of Cylinders Exhaust Gas Temperatures [°C], average values

Engine Speed: 1200 rpm

Load [%]	Carburetion System	Cyliner Number							
		1	2	3	4	5	6	7	8
100	Gasoline	646	578	638	621	638	671	531	658
	IMPCO	678	681	659	664	638	685	564	670
	BEAM	659	678	654	662	645	671	561	679
	A.F.S.	660	688	662	657	645	668	552	678
	OXIN	615	632	609	607	594	613	507	622
66	Gasoline	620	530	633	618	627	635	512	644
	IMPCO	597	602	604	584	576	598	495	605
	BEAM	586	604	598	594	580	593	498	605
	A.F.S.	582	604	595	589	583	589	491	601
	OXIN	621	642	641	633	607	621	533	646
33	Gasoline	596	504	622	612	628	628	494	642
	IMPCO	569	566	580	557	558	571	489	572
	BEAM	556	578	570	561	559	562	494	571

	A.F.S	562	571	569	569	553	565	490	566
	OXIN	603	618	621	605	598	605	511	621
	Gasoline	607	503	600	625	611	613	490	614
	IMPCO	513	535	543	516	519	498	510	548
~0	BEAM	549	531	537	523	546	523	511	520
	A.F.S.	530	536	544	530	523	539	511	551
	OXIN	613	585	589	583	579	601	527	587

Table 4-21: Distribution of Cylinders Exhaust Gas Temperatures [°C], average values

Engine Speed: 2400 rpm

Load [%]	Carburetion System	Cyliner Number							
		1	2	3	4	5	6	7	8
100	Gasoline	726	696	744	741	730	725	687	741
	IMPCO	748	755	768	738	749	745	682	730
	BEAM	741	752	746	743	741	745	687	745
	A.F.S.	752	750	748	745	717	747	682	743
	OXIN	743	739	731	719	727	729	681	721
66	Gasoline	766	719	775	760	751	774	713	772
	IMPCO	726	733	715	728	724	722	692	721
	BEAM	731	725	720	731	709	728	691	713
	A.F.S.	729	735	738	728	724	729	689	727
	OXIN	732	737	735	737	725	723	695	733
	Gasoline	750	690	765	747	735	766	689	763
	IMPCO	702	679	677	673	677	701	650	677

33	BEAM	705	707	712	705	681	712	680	705
	A.F.S.	702	708	717	697	699	687	674	709
	OXIN	725	726	737	721	710	716	699	725
	Gasoline	736	632	750	740	731	750	639	744
	IMPCO	665	644	704	677	656	677	636	684
~0	BEAM	656	656	690	687	653	678	639	678
	A.F.S.	661	654	690	685	660	677	635	678
	OXIN	693	683	717	707	691	703	656	706

Table 4-22: Distribution of Cylinders Exhaust Gas Temperatures [°C], average values

Engine Speed: 3600 rpm

Load [%]	Carburetion System	Cyliner Number							
		1	2	3	4	5	6	7	8
100	Gasoline	881	797	822	805	869	887	869	826
	IMPCO	842	843	832	805	831	852	771	795
	BEAM	818	841	839	808	827	811	771	817
	A.F.S.	826	834	827	803	806	820	767	812
	OXIN	824	859	827	828	821	813	782	809
66	Gasoline	837	772	839	833	818	838	784	823
	IMPCO	804	804	808	791	790	792	781	795
	BEAM	812	819	813	801	806	811	773	798
	A.F.S.	820	819	819	809	806	816	778	802
	OXIN	833	838	862	851	816	821	813	820
	Gasoline	846	769	851	835	821	850	789	832
	IMPCO	783	782	786	774	774	782	764	780

33	BEAM	788	782	783	782	769	792	764	773
	A.F.S.	790	797	799	783	787	791	762	788
	OXIN	823	817	828	828	805	811	809	800
	Gasoline	811	740	829	826	806	825	734	800
	IMPCO	735	726	740	730	739	747	729	727
~0	BEAM	745	743	765	760	746	772	744	747
	A.F.S.	754	751	776	758	764	758	746	752
	OXIN	810	812	824	816	814	820	803	807

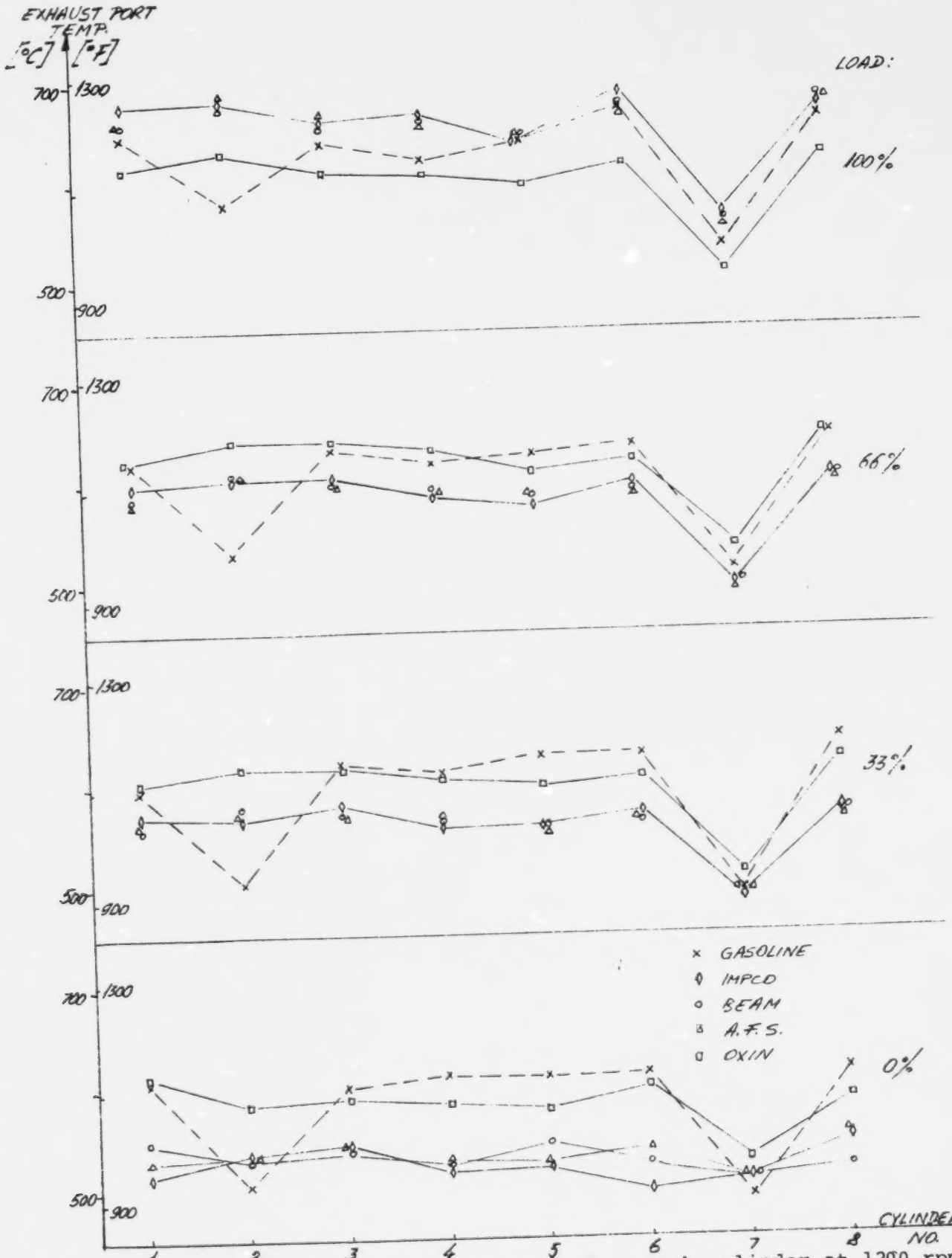


Figure 4-14: Temperature of exhaust gas from each cylinder at 1200 rpm.

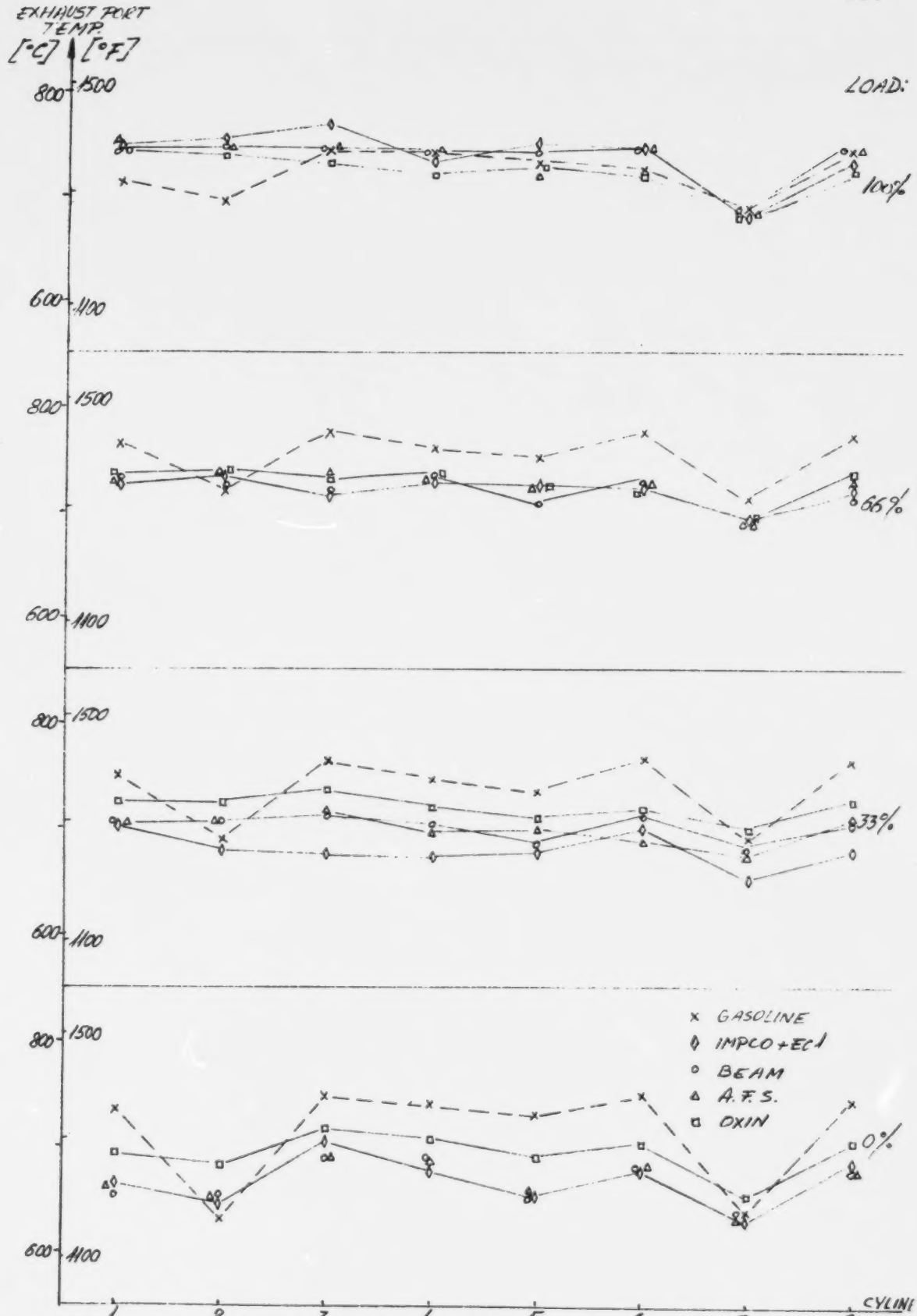


Figure 4-15: Temperature of exhaust gas from each cylinder at 2400 rpm.

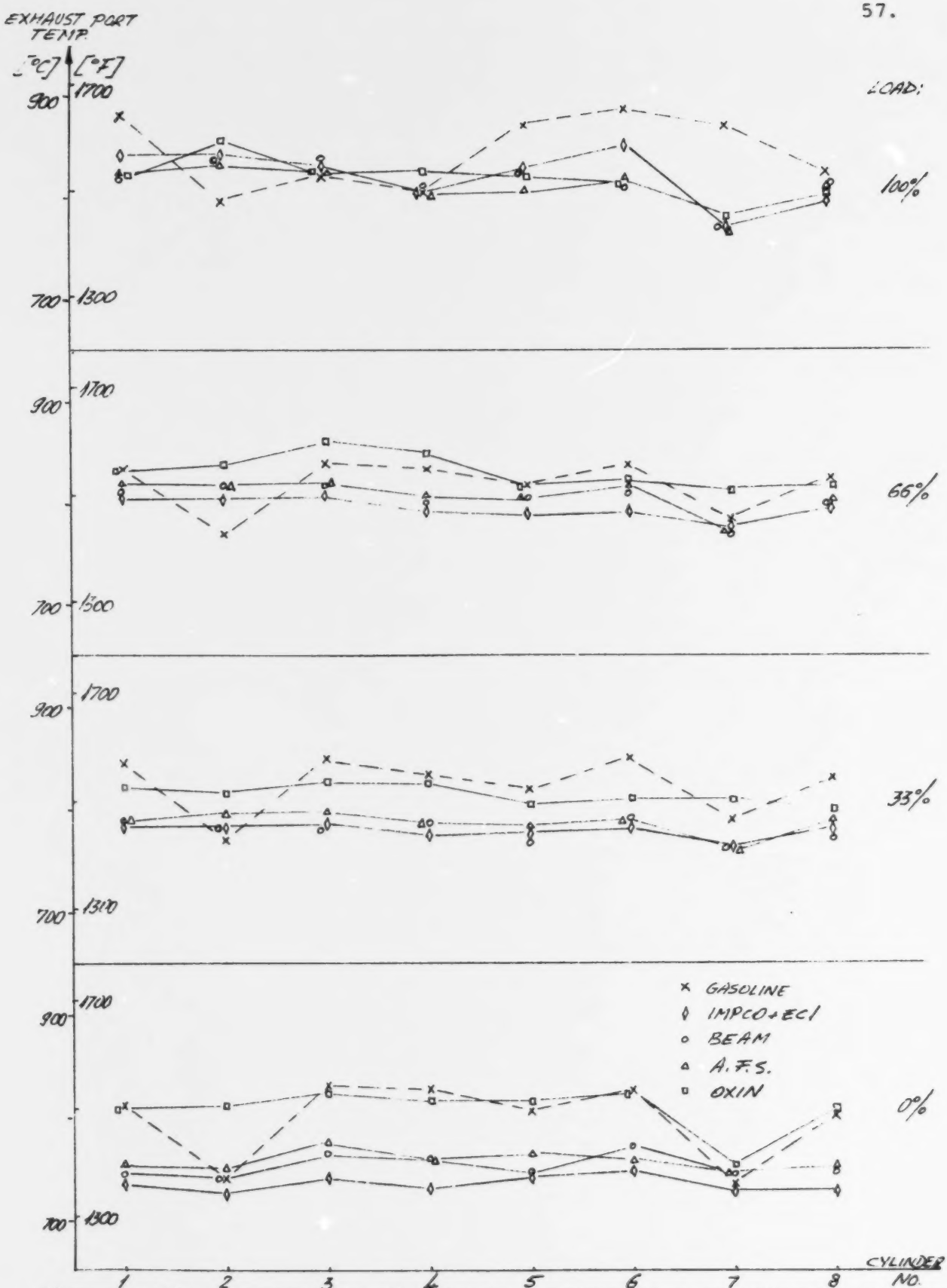


Figure 4-16: Temperature of exhaust gas from each cylinder at 3600 rpm.

Table 4-23: HC Emission

$$\left[\frac{\text{PPM-}CH_4\text{equivalent}}{\%\text{ vs. gasoline}}\right]$$, average values

Load [%]	Carburetion System	Engine Speed [rpm] 1200	1800	2400	3000	3600
100	Gasoline	3130	3040	2043	2130	1492
	IMPCO	415	1113	1125	850	750
		-93.2	-63.4	-44.9	-60.1	-49.7
	BEAM	900	670	650	600	595
		-71.25	-77.96	-68.18	-71.83	-60.12
	A.F.S.	887	882	750	625	445
		-71.66	-70.99	-63.29	-70.66	-70.17
	OXIN	1538	1255	925	335	58
		-50.86	-58.72	-54.72	-84.27	-96.11
66	Gasoline	2308	2638	1648	1380	1925
	IMPCO	1063	663	1063	1075	875
		-53.9	-74.9	-35.5	-22.1	-54.5
	BEAM	1125	941	935	840	710
		-51.26	-64.33	-43.26	-39.13	-63.12

	A.F.S.	1150	994	975	937	865
		-50.17	-62.32	-40.84	-32.10	-55.06
	OXIN	925	530	500	58	16
		-59.92	-79.91	-69.66	-95.80	-99.17
	Gasoline	1440	1538	1668	1360	892
	IMPCO	900	575	515	580	888
		-37.5	-62.6	-69.1	-57.4	-0.4
33	BEAM	764	611	660	558	420
		-46.94	-60.27	-60.43	-58.97	-52.91
	A.F.S.	768	607	712	775	530
		-46.67	-60.53	-57.31	-43.01	-40.58
	OXIN	510	265	245	30	38
		-64.58	-82.77	-85.31	-97.79	-95.74
	Gasoline	530	378	506	1025	1667
	IMPCO	800	500	355	165	103
		+50.9	+32.3	-29.8	-83.9	-93.8
~0	BEAM	485	378	256	115	75
		-8.49	0.00	-49.41	-88.78	-95.50
	A.F.S.	545	365	218	104	79
		+2.83	-3.44	-56.92	-89.85	-95.26
	OXIN	315	170	126	23	25
		-40.57	-55.03	-75.10	-97.76	-98.50

- Gasoline with emissions controls, propane without.

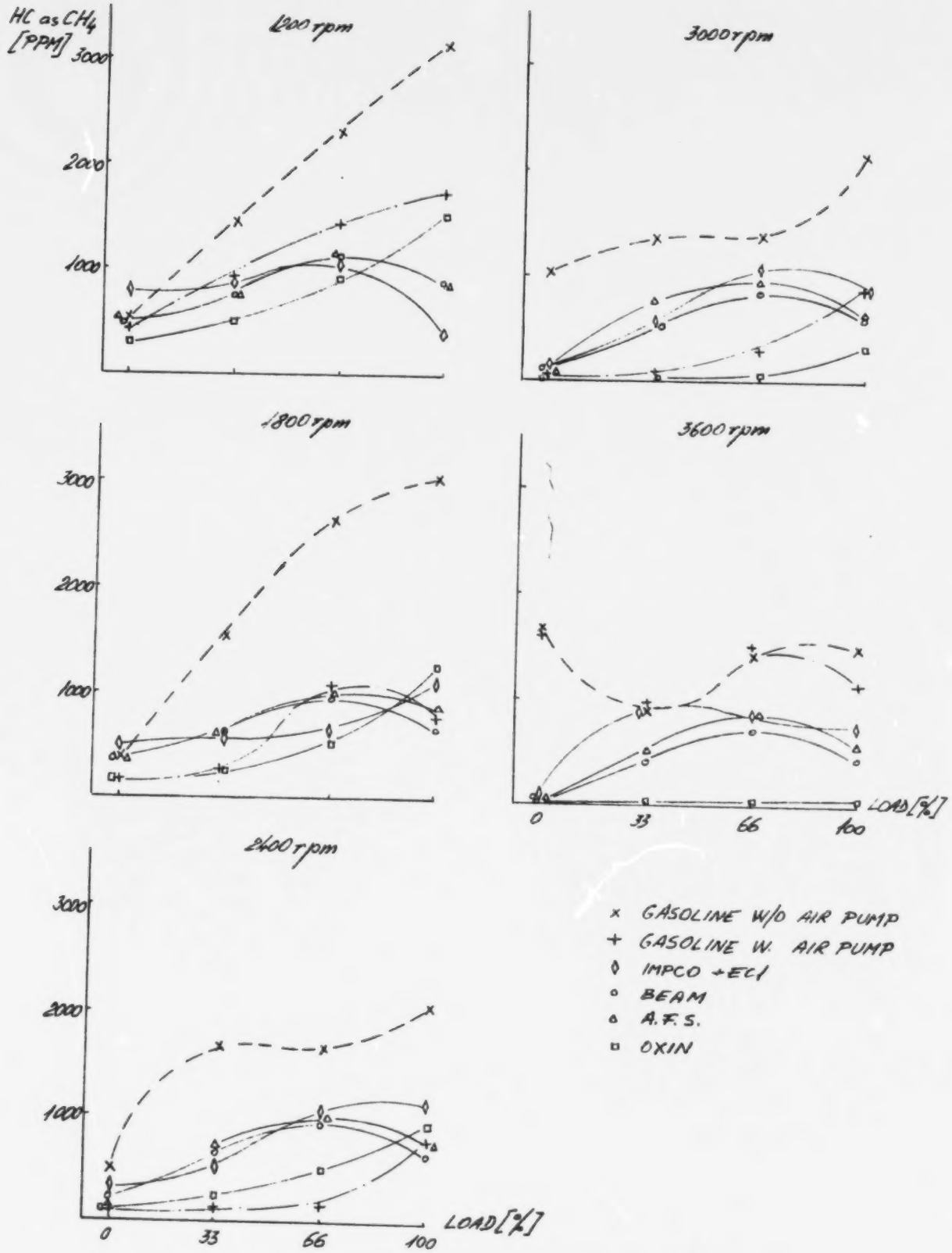


Figure 4-17: HC emission at different speeds and loads (gasoline with emissions controls, propane without).

Table 4-24: NO Emission

$$\left[\frac{\text{PPM}}{\%\text{ vs. gasoline}}\right]$$, average values

Load [%]	Carburetion System	Engine Speed [rpm] 1200	1800	2400	3000	3600
100	Gasoline	840	1053	755	1293	1658
	IMPCO	1213	1663	1788	2550	2400
		+44.4	+57.9	+136.8	+97.2	+44.8
	BEAM	1900	1888	2200	2389	2500
		+126.19	+79.30	+191.39	+84.76	+50.78
	A.F.S.	2013	1975	2437	2600	2500
		+139.64	+87.56	+222.78	+101.08	+50.78
	OXIN	813	1500	2650	265	1863
		-3.21	+42.45	+250.99	-79.51	+12.36
66	Gasoline	1815	665	977	1085	1183
	IMPCO	465	1738	3000	2900	2950
		-74.4	+161.4	+207.1	+167.3	+149.4
	BEAM	1938	2638	3500	3600	3600
		+6.78	+296.69	+258.24	+231.80	+204.31

	A.F.S.	1987	2860	3500	3650	3650
		+9.48	+330.08	+258.24	+236.41	+208.54
	OXIN	1850	1950	2900	2088	1500
		+1.93	+193.23	+196.83	+92.44	+26.80
	Gasoline	993	977	503	420	543
	IMPCO	325	575	515	580	888
		-67.3	-41.1	+2.4	+38.1	+63.5
33	BEAM	595	1197	2350	2700	2850
		-40.08	+22.52	+367.20	+542.86	+424.86
	A.F.S.	588	1285	2500	2850	3000
		-40.79	+31.53	+397.02	+578.57	+452.49
	OXIN	395	800	1400	1013	834
		-60.22	-18.12	+178.33	+141.19	+53.59
	Gasoline	101	223	303	267	228
	IMPCO	47	77	113	270	485
		-53.5	-65.5	-62.7	+1.1	+112.7
~0	BEAM	60	120	270	540	888
		-40.59	-46.19	-10.89	+102.25	+289.47
	A.F.S.	30	121	270	623	1075
		-70.30	-45.74	-10.89	+133.33	+371.49
	OXIN	33	100	170	230	350
		-67.33	-55.16	-43.89	-13.86	+53.51

- Gasoline with emissions controls, propane without.

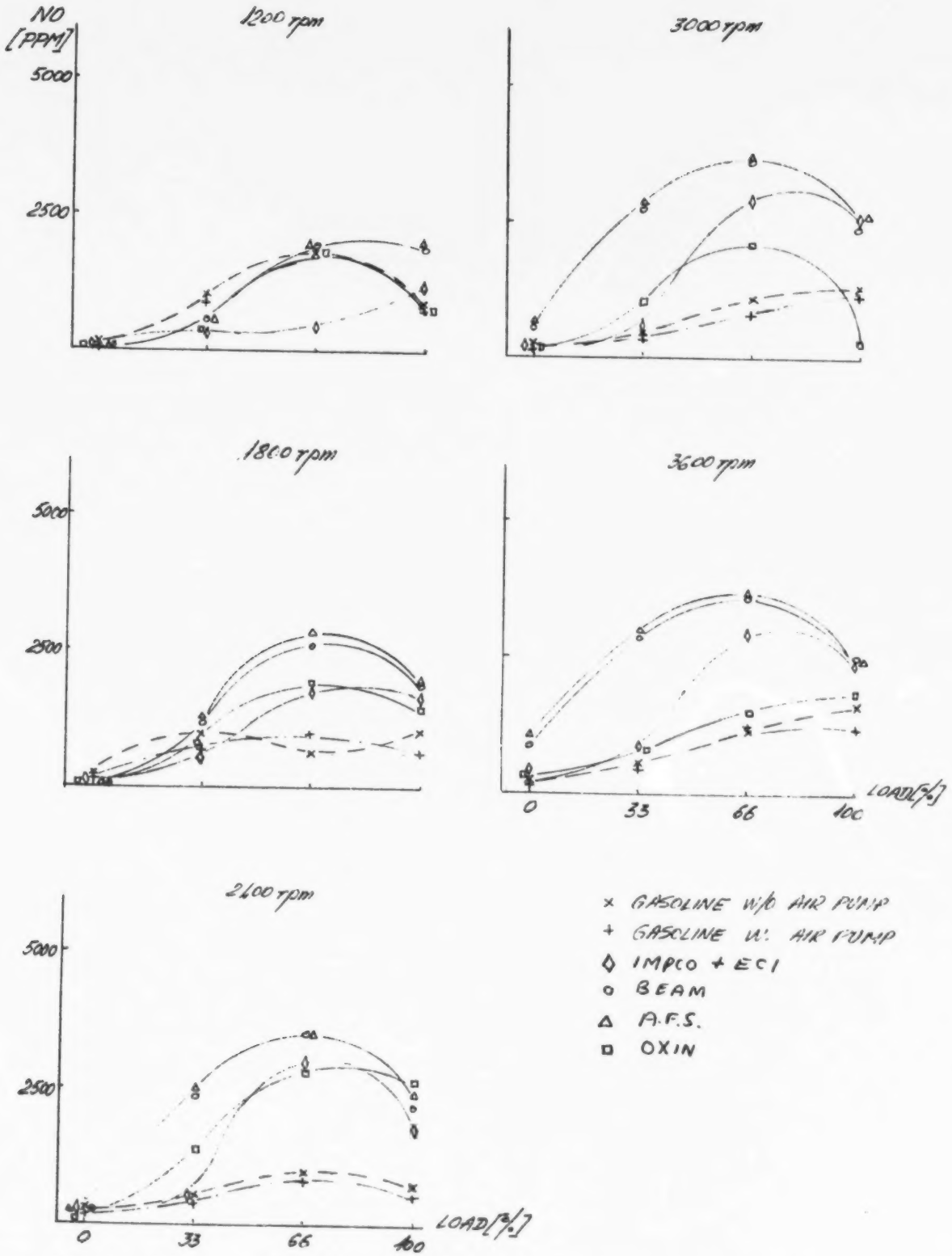


Figure 4-18: NO emission at different speeds and loads (gasoline with emissions controls, propane without).

Table 4-25: O_2 Emission

[%], Average Values

Load [%]	Carburetion System	Engine Speed [rpm]				
		1200	1800	2400	3000	3600
100	Gasoline	0.30	0.10	0.03	0.07	0.10
	IMPCO	2.35	0.10	0.10	0.35	0.10
	BEAM	0.55	0.60	0.50	0.35	0.20
	A.F.S.	0.85	0.58	0.40	0.30	0.15
	OXIN	0.30	0.22	0.30	0.80	0.50
66	Gasoline	1.05	0.45	0.30	0.23	0.27
	IMPCO	4.30	2.45	0.60	0.30	0.30
	BEAM	1.80	1.10	0.65	0.50	0.40
	A.F.S.	2.05	1.09	0.55	0.35	0.25
	OXIN	1.10	1.38	1.35	1.80	1.45
33	Gasoline	1.33	0.63	0.43	0.30	0.33
	IMPCO	3.75	3.75	2.95	1.20	0.40
	BEAM	2.40	1.85	1.25	0.90	0.65

	A.F.S.	2.55	1.85	1.00	0.60	0.55
	OXIN	2.75	2.15	1.75	2.20	2.30
	Gasoline	2.63	1.28	0.80	0.17	0.10
	IMPCO	1.45	3.80	3.85	3.45	3.00
~0	BEAM	2.25	2.60	2.15	1.80	1.10
	A.F.S.	3.70	2.70	2.15	1.50	0.90
	OXIN	3.70	2.98	2.55	2.0	1.75

- Gasoline with emissions controls, propane without.

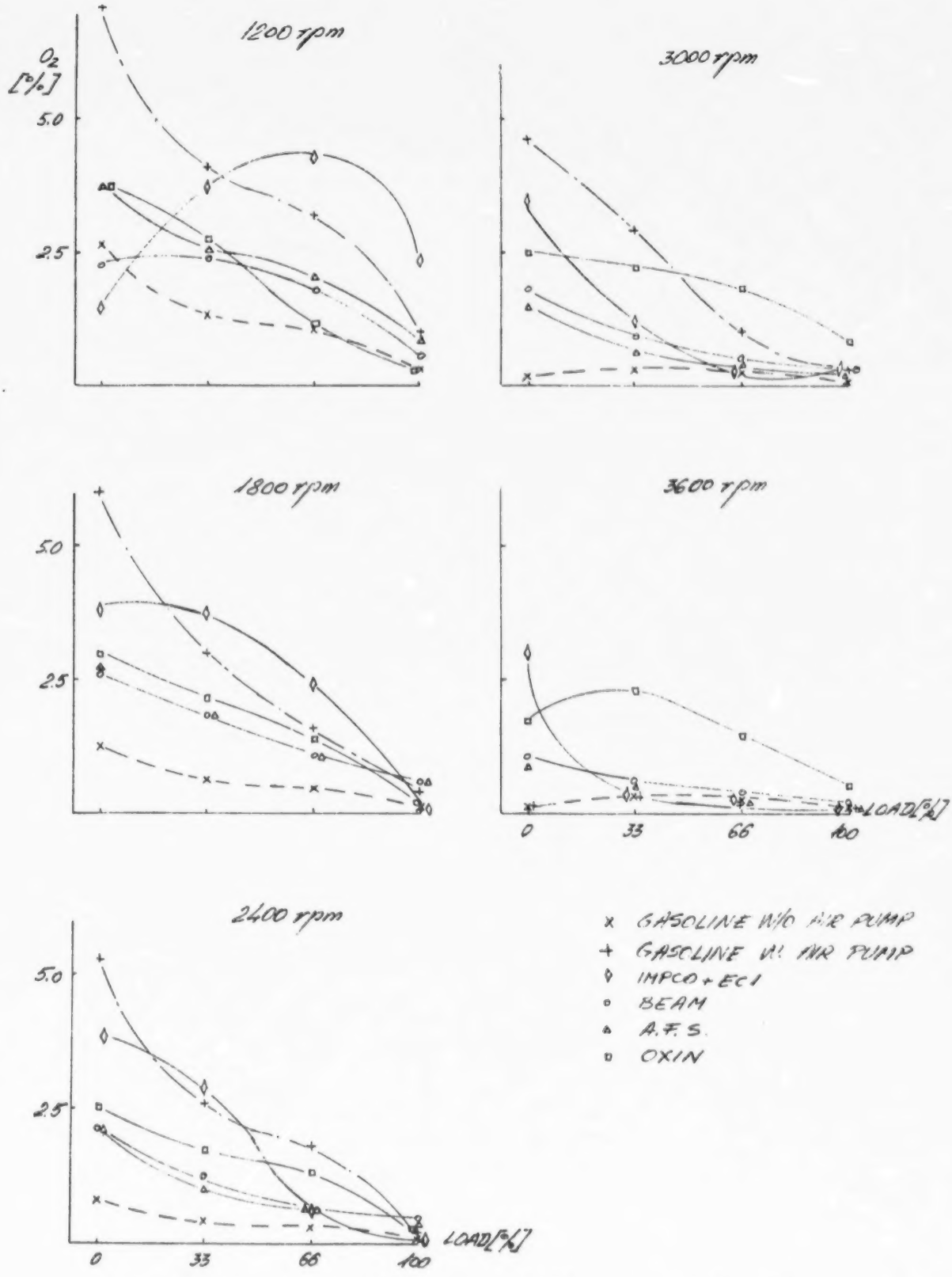


Figure 4-19: O_2 emissions at different speeds and loads (gasoline with emissions controls, propane without).

Table 4-26: CO Emission

$[\frac{[\%]}{\%\text{ vs. gasoline}}]$, average values

Load [%]	Carburetion System	Engine Speed [rpm] 1200	1800	2400	3000	3600
100	Gasoline	4.33	3.80	5.40	3.63	3.43
	IMPCO	0.13	1.33	1.75	1.38	1.69
		-97.00	-65.00	-67.60	-62.00	-50.70
	BEAM	0.36	0.57	1.18	1.42	1.32
		-91.69	-85.00	-78.15	-60.88	-61.52
	A.F.S.	0.21	0.52	1.00	1.29	1.31
		-95.15	-86.32	-81.48	-64.46	-61.81
	OXIN	3.00	1.70	1.07	0.42	0.51
		-30.72	-55.26	-80.19	-88.43	-85.13
66	Gasoline	0.92	1.92	1.15	1.06	1.32
	IMPCO	0.11	0.14	0.57	1.14	1.13
		-88.00	-92.70	-50.40	+7.50	-14.40
	BEAM	0.08	0.09	0.16	0.32	0.54
		-91.30	-95.31	-86.09	-69.81	-59.09

	A.F.S	0.06	0.07	0.15	0.28	0.42
		-93.48	-96.35	-86.96	-73.58	-68.18
	OXIN	0.14	0.12	0.11	0.09	0.06
		-84.78	-93.75	-90.43	-91.51	-95.45
33	Gasoline	0.24	0.82	1.17	1.36	0.69
	IMPCO	0.09	0.14	0.13	0.32	0.72
		-62.50	-82.90	-88.90	-76.50	+4.30
	BEAM	0.08	0.09	0.12	0.20	0.30
		-66.67	-89.02	-89.74	-85.29	-56.52
	A.F.S	0.07	0.10	0.12	0.18	0.22
		-70.83	-87.80	-89.74	-86.76	-68.12
	OXIN	0.10	0.10	0.12	0.08	0.06
		-58.33	-87.80	-89.74	-94.12	-91.30
~0	Gasoline	0.13	0.24	0.61	1.25	2.05
	IMPCO	0.81	0.10	0.14	0.13	0.12
		+523.10	-58.30	-77.00	-89.60	-94.10
	BEAM	0.08	0.09	0.11	0.12	0.12
		-38.46	-62.50	-81.97	-90.40	-94.15
	A.F.S.	0.06	0.08	0.10	0.12	0.12
		-53.85	-66.67	-83.61	-90.40	-94.15
	OXIN	0.07	0.07	0.10	0.06	0.04
		-46.15	-70.83	-83.61	-95.20	-98.05

- Gasoline with emissions controls, propane without.

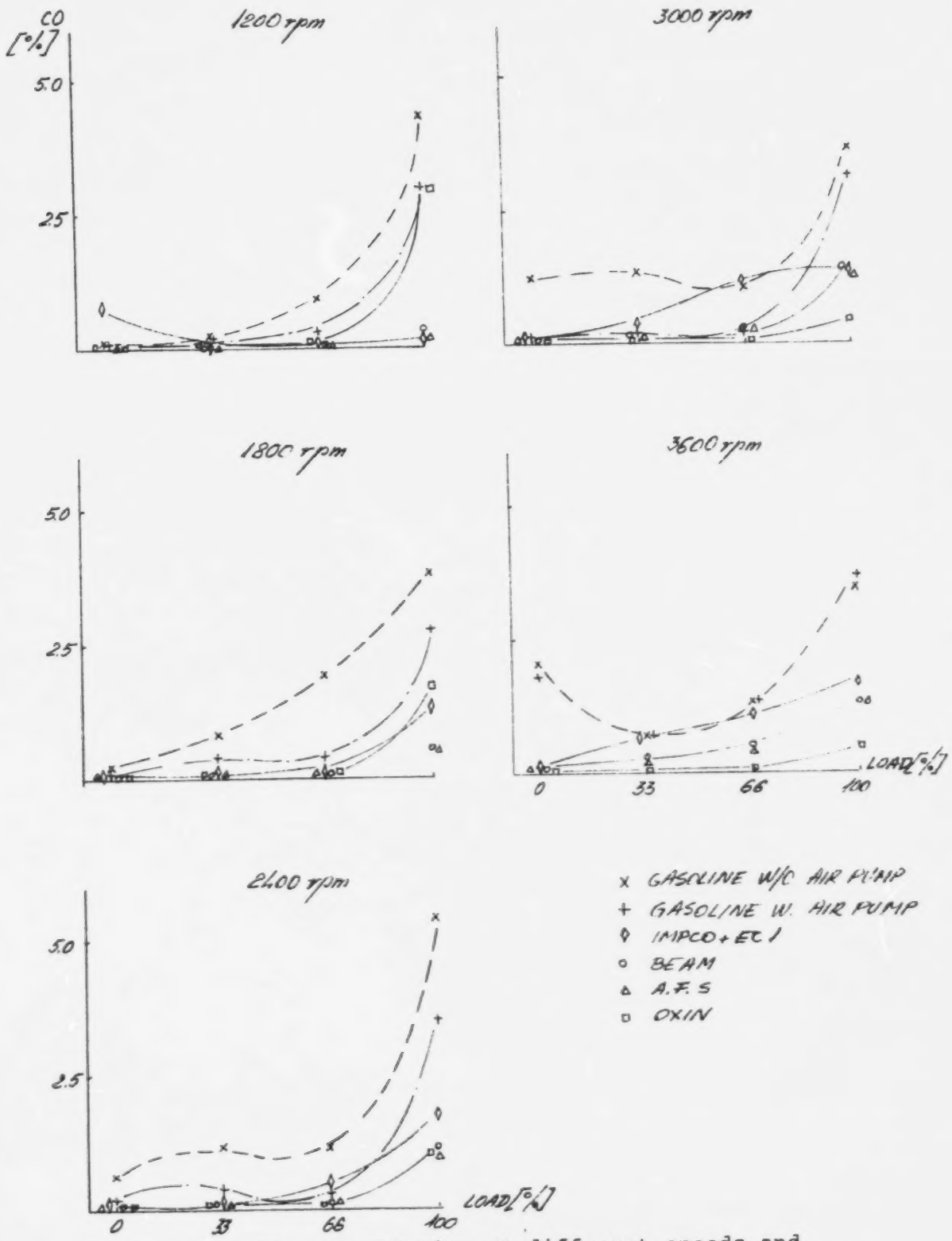


Figure 4-20: CO emission at different speeds and loads (gasoline with emissions controls, propane without).

Table 4-27: CO_2 Emission

[%], Average Values

Load [%]	Carburetion System	Engine Speed [rpm] 1200	1800	2400	3000	3600
100	Gasoline	11.80	12.40	11.43	12.70	13.23
	IMPCO	11.25	11.80	11.95	12.10	12.00
	BEAM	12.00	11.75	11.30	11.30	11.40
	A.F.S.	12.30	12.20	12.00	11.80	12.00
	OXIN	11.10	12.00	12.20	12.20	12.30
66	Gasoline	13.55	13.35	14.00	14.37	14.40
	IMPCO	10.20	11.30	12.40	12.25	12.05
	BEAM	11.40	11.75	12.00	12.10	12.10
	A.F.S.	11.50	12.20	12.50	12.50	12.50
	OXIN	12.40	12.10	12.10	11.80	12.10
33	Gasoline	13.50	13.70	14.00	14.07	14.70
	IMPCO	10.40	10.20	11.10	12.15	12.15
	BEAM	11.10	11.25	11.60	12.00	11.90

	A.F.S.	11.30	11.80	12.50	12.40	12.50	
	OXIN	11.30	11.80	11.80	11.50	11.40	
	Gasoline	12.53	13.73	13.87	14.40	14.27	
	IMPCO	11.30	10.75	10.80	10.95	10.95	
~0	BEAM	11.20	10.90	11.30	11.40	11.90	11.20
	A.F.S.	10.80	11.30	11.60	12.00	12.50	12.40
	OXIN	11.05	11.50	11.40	11.80	12.20	

- Gasoline with emissions controls, propane without.

Table 4-28: Emissions for Gasoline Carburetion System, With Air Pump Active

Load [%]	Emission	U.M.	Engine Speed [rpm]				
			1200	1800	2400	3000	3600
100	HC	PPM CH_4	1720	765	780	860	1136
	NO	PPM	855	655	560	1230	1225
	O_2	%	1.00	0.40	0.20	0.30	0.10
	CO	%	3.00	2.75	3.50	3.10	3.70
	CO_2	%	12.30	12.80	12.40	13.00	12.70
66	HC	PPM CH_4	1440	1040	165	300	1663
	NO	PPM	1880	1030	830	780	1250
	O_2	%	3.20	1.60	1.80	1.00	0.20
	CO	%	0.30	0.40	0.30	0.20	1.28
	CO_2	%	12.20	13.40	13.10	14.00	14.20
33	HC	PPM CH_4	930	265	134	96	988
	NO	PPM	910	730	395	380	510
	O_2	%	4.10	3.00	2.60	2.90	0.40
	CO	%	0.22	0.41	0.38	0.20	0.74
	CO_2	%	11.60	12.20	12.50	12.60	14.50

	HC	PPM CH_4	420	186	104	59	1625
	NO	PPM	68	158	230	185	240
~0	O_2	%	7.15	6.00	5.30	4.60	0.10
	CO	%	0.10	0.13	0.20	0.14	1.78
	CO_2	%	9.70	10.40	10.70	11.30	14.20

Table 4-29: Air-Fuel Ratio

(A/F Stoichiometric ~ 14.59 for Gasoline

~ 15.69 for Propane)

average Values

Load [%]	Carburetion System	Engine Speed [rpm] 1200	1800	2400	3000	3600
100	Gasoline	12.77	12.89	12.32	12.97	13.20
	IMPCO	17.48	15.02	14.81	15.20	14.90
	BEAM	15.82	15.78	15.40	15.18	15.07
	A.F.S.	16.12	15.76	15.42	15.23	15.14
	OXIN	14.29	14.84	15.31	15.98	15.80
66	Gasoline	14.74	13.83	14.15	14.23	14.05
	IMPCO	19.30	18.00	15.77	15.27	15.30
	BEAM	16.97	16.46	16.05	15.87	15.70
	A.F.S.	17.17	16.38	16.12	15.77	15.63
	OXIN	16.33	16.65	16.66	17.08	16.77
33	Gasoline	15.28	14.51	14.20	14.07	14.41
	IMPCO	18.78	18.95	18.00	16.39	15.47
	BEAM	17.50	17.08	16.56	16.25	16.03

	A.F.S.	17.60	17.01	16.34	15.99	15.97
	OXIN	17.79	17.23	16.97	17.41	17.51
	Gasoline	16.47	15.31	14.78	14.21	13.68
	IMPCO	16.22	18.78	18.79	18.46	18.11
~0	BEAM	17.38	17.69	17.32	17.03	16.45
	A.F.S.	18.70	17.72	17.28	16.73	16.27
	OXIN	18.66	17.97	17.65	17.19	16.96

Table 4-30: Equivalence Air-Fuel Ratio $(\frac{A/F}{A/F\ stoich.})$, average values

Load [%]	Carburetion System	Engine Speed [rpm] 1200	1800	2400	3000	3600
100	Gasoline	0.88	0.88	0.84	0.89	0.90
	IMPCO	1.11	0.96	0.94	0.97	0.95
	BEAM	1.01	1.00	0.98	0.97	0.96
	A.F.S.	1.03	1.00	0.98	0.97	0.96
	OXIN	0.91	0.95	0.98	1.02	1.01
66	Gasoline	1.01	0.95	0.97	0.98	0.96
	IMPCO	1.23	1.15	1.01	0.97	0.98
	BEAM	1.08	1.05	1.02	1.01	1.00
	A.F.S.	1.09	1.02	1.03	1.01	1.00
	OXIN	1.04	1.06	1.06	1.09	1.07
33	Gasoline	1.05	0.99	0.97	0.96	0.99
	IMPCO	1.20	1.21	1.15	1.04	0.99
	BEAM	1.12	1.09	1.06	1.04	1.02

	A.F.S.	1.12	1.08	1.04	1.02	1.02
	OXIN	1.13	1.10	1.08	1.11	1.12
	Gasoline	1.13	1.05	1.01	0.97	0.94
	IMPCO	1.03	1.20	1.20	1.18	1.15
~0	BEAM	1.11	1.13	1.10	1.09	1.05
	A.F.S.	1.19	1.13	1.10	1.07	1.04
	OXIN	1.19	1.15	1.12	1.10	1.08

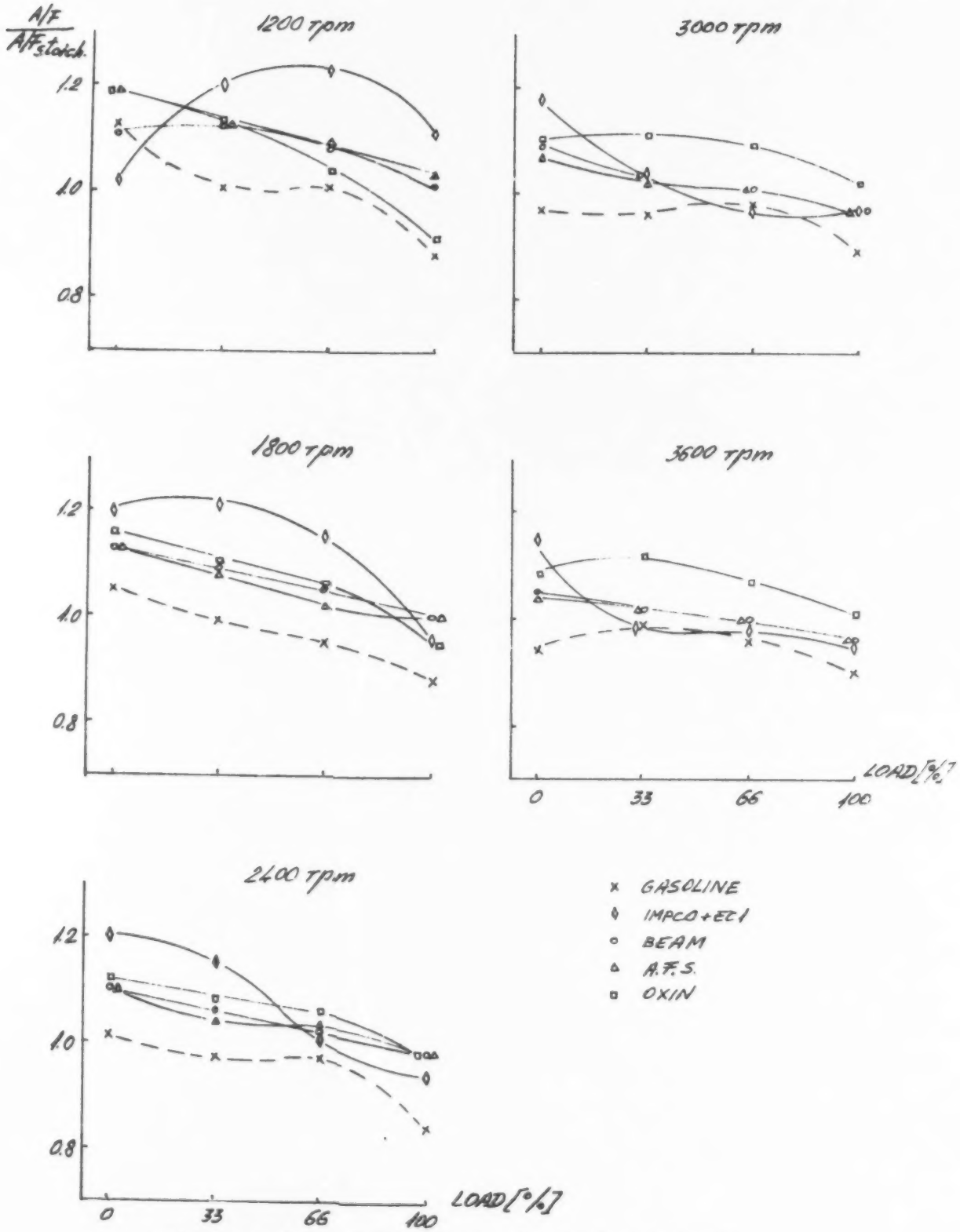


Figure 4-21: Equivalent air-fuel ratio at different loads and speeds.

5. SYSTEM OPTIMIZATION

5.1 PROCEDURE

The influence of timing and air-fuel ratio is analyzed according to the procedure described here, for full and partial loads.

5.1.1 Influence of timing at full load (WOT) - see Figure 5-1:

- set ignition manually, isolating the vacuum advance and moving the body of the distributor until the desired timing angle is read
- stabilize on lowest desired speed with spark retarded from the best torque timing
- record torque and timing
- advance spark 2 degrees and record torque, maintaining the speed constant
- repeat until a 2-degree advance shows no improvement in torque
- retard half interval, check that torque and speed are unchanged, run and record data at determined minimum for best torque (MBT) advance
- repeat in speed increments to maximum test speed

5.1.2 Influence of air-fuel ratio at full load (WOT) - see Figure 5-2:

- adjust carburetion system, controlling the reference pressure in the second stage of

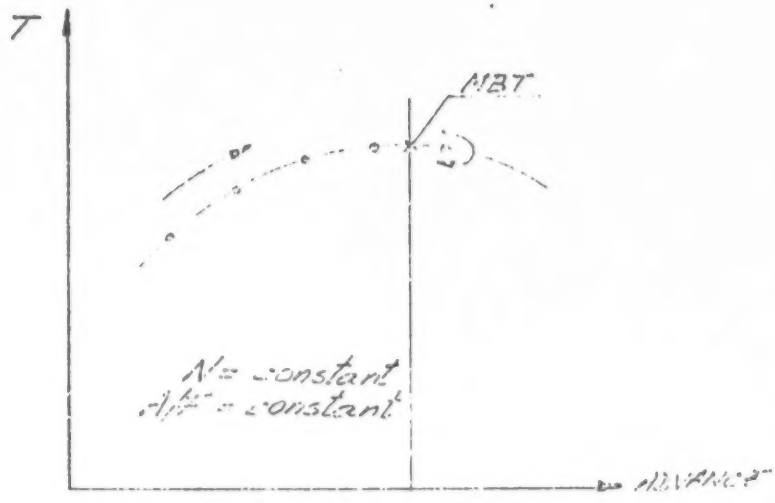


Figure 5-1: Principle of Timing Optimization at Full Load, for MBT (minimum for best torque)

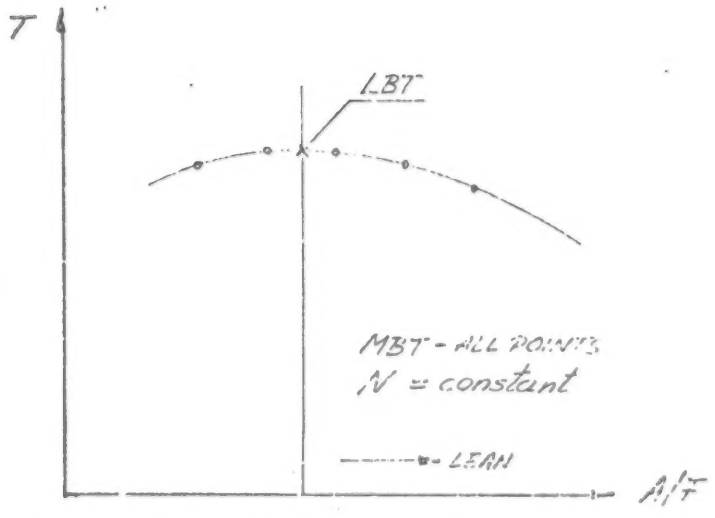


Figure 5-2: Principle of Air-Fuel Ratio Optimization at Full Load, for LBT (leanest for best torque)

regulator (IMPCO) or the opening of power valve between vaporizer/regulator and carburettor

- set ignition manually as in 5.1.1
- stabilize at lowest desired speed with the carburetion system richer than leanest for best torque (LBT) and spark retarded from MBT setting
- record torque, timing and A/F ratio
- determine and record MBT timing at constant A/F ratio, as per 5.1.1
- lean air-fuel mixture
- readjust and record MBT timing and new A/F ratio
- record torque
- lean air-fuel mixture and readjust MBT timing until torque falls below previous value
- adjust mixture reacher, midway between last two settings and readjust MBT timing
- check that torque is equal to previous maximum value and speed is unchanged, run and record data at determined LBT
- repeat in speed increments to maximum test speed

5.1.3 Influence of timing at partial loads (2/3 and 1/3 of maximum at WOT) - see Figure 5-3

- set ignition manually
- stabilize at lowest desired speed, 2/3 or 1/3 of the MBT torque, with spark retarded from the point of minimum specific fuel consumption
- run the test and compute BSFC

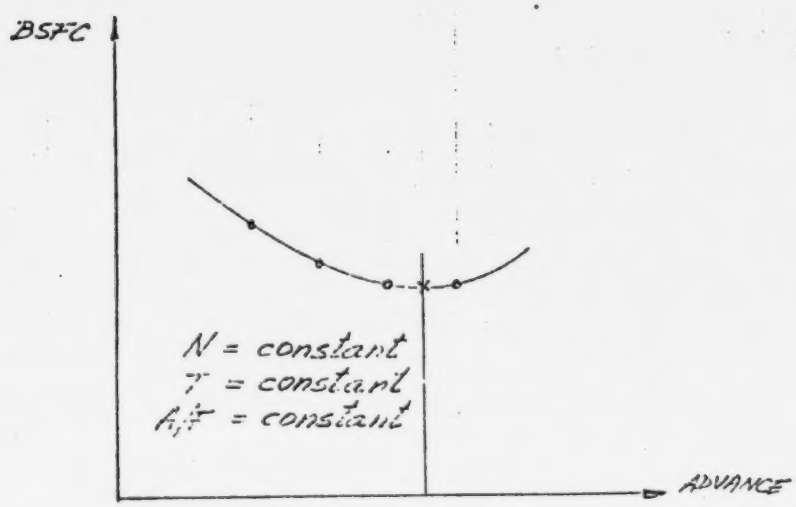


Figure 5-3: Principle of Timing Optimization at Partial Loads, for Minimum BSFC (brake specific fuel consumption)

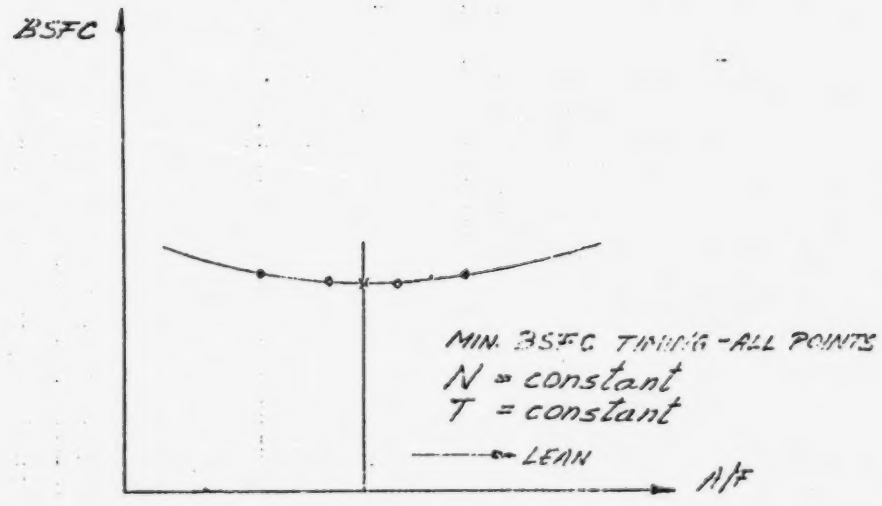


Figure 5-4: Principle of Air-Fuel Ratio Optimization at Partial Loads, for Minimum BSFC

- advance spark 3 degrees, run the test maintaining speed and torque constant and compute BSFC
- repeat until BSFC reaches a minimum and starts to rise again
- retard to the point of minimum BSFC and run the test to check that the value of BSFC is unchanged
- repeat in speed increments to maximum test speed

5.1.4 Influence of air-fuel ratio at partial loads (2/3 and 1/3 of maximum at WOT) - see Figure 5-4

- adjust carburetion system as per 5.1.2
- set ignition manually
- stabilize at lowest desired speed, 2/3 or 1/3 of the MBT torque, the carburetion system richer and spark retarded from the values necessary for minimum BSFC
- record timing and A/F ratio, run test and compute BSFC
- determine timing for minimum BSFC as per 5.1.3
- lean air-fuel mixture
- determine timing for minimum BSFC at new A/F ratio
- lean air-fuel mixture and readjust the timing for minimum BSFC until BSFC reaches a minimum and starts to rise again

- retard to the midpoint between the last two tests, check that the values are unchanged
- repeat in speed increments to maximum test speed

5.2 OPTIMIZATION RESULTS

5.2.1. Full load optimization

The results of MBT (minimum for best torque) timing optimization at full load are summarized in Figure 5-5 and Table 5-1, for three different air-fuel ratios.

An increase of timing from 7° to 28° at 1200 rpm is generating the most significant increase in torque and power output - 29.54%, without any other modifications. At 2400 rpm the commercial calibration of timing is very close to the optimum (28°), leaving no room for further improvement. Part of the higher torque obtained by OXIN system at low speeds is due to a timing value closer to the optimum (see Figure 5-9).

The influence of air-fuel ratio is represented graphically in Figures 5-6 and 5-7. Enriching the air-fuel mixture to approx. 0.875 equivalence ratio, the torque reaches a maximum, with a correspondent increase in power output of up to 7.24% over commercial calibration. The price is an increase of up to 15.63% in specific fuel consumption. Leaning the air-fuel ratio to approx. 1.15 ÷ 1.30 equivalence ratio reduces the specific fuel consumption up to 6.33%, but at a reduction of power output reaching 13.62%. As in the previous Projects, a mixture air-fuel of approx. 0.925 ÷ 0.935 equivalence ratio will produce a power comparable with gasoline, reasonable fuel consumption and will avoid the increased exhaust temperatures associated with stoichiometric mixtures.

This is the second reason for the OXIN system higher torque at low speeds (0.91 equivalence ratio, against 1.01 ÷ 1.11 for the rest of propane carburetion systems).

5.2.2 Partial Load Optimization

The search for optimum timing at partial loads is summarized in Figure 5-8. The characteristics are generally flat, showing little sensitivity to timing variation around the optimum values. The results of timing optimization are compared with the two calibration used commercially in this Project for an unchanged air-fuel ratio, in Figure 5-9. The big difference between the advances used in practice and the optimum values in the range 1200 to 1800 rpm has to be mentioned, with all the negative consequences on power and economy.

The results of air-fuel ratio optimization at optimum timing are summarized in Figure 5-10 and Table 5-2. The curves show a strong dependence between BSFC and the A/F ratio, expecially at higher loads and speeds, where such a behaviour is even more important due to the higher powers involved. The optimum A/F ratio range between 18.25 and 21.00 (1.17 to 1.35 equivalence ratio), at increased advance (35 to 53°), and with beneficial effects on specific fuel consumption (6.13 to 15.68% improvement vs. commercial calibration of A/F and timing, mass base).

The overall impact of optimization is presented in Table 5-3 and Figure 5-11. The use of optimum air-fuel ratio and timing at partial loads results in a supplementary energy efficiency increase of 3.41 to 18.27% against the average for the 4 systems tested.

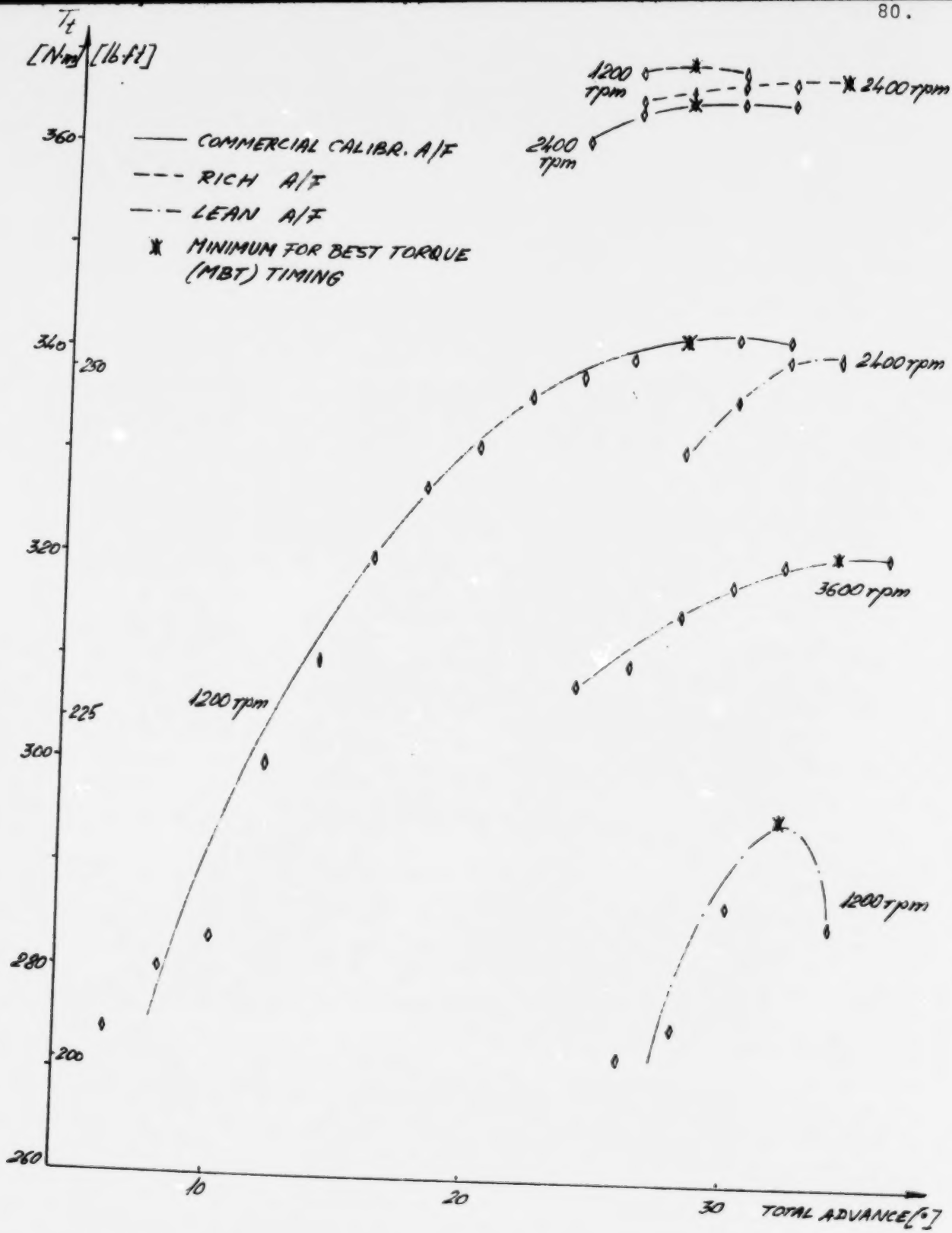


Figure 5-5: Timing Optimization at Full Load, for MBT (Minimum for Best Torque), on FORD 6.1 L LIMA Engine, propane fuel.

Table 5-1: WOT Performance at Optimum Timing (MBT)
(change vs. commercial timing and A/F ratio on IMPCO system)

Engine A/F Calibration:		Commercial		Rich**		Lean **	
Speed	rpm	1200*	2400	1200	2400	1200	2400
Observed Torque	N.m	342	365	369	368	296	340
Corrected Power	kW	43.24	91.76	46.37	92.74	37.35	85.45
Change	%	+29.54	-	+7.24	+1.07	-13.62	-6.88
OBSFC	g/kW.h	251.22	272.08	290.48	299.86	255.4	254.87
Change	%	-22.30	-	+15.63	+10.21	+1.66	-6.33
Optimum Timing	0	28	28	28	34	32	32
A/F	-	17.71	14.33	13.73	13.16	20.31	17.03
Change A/F	-	-	-	-3.98	-1.17	+2.60	+2.70
Average Exhaust Temperature	°C	416	600	415	573	428	611

*vs. commercial timing (7°)
**vs. optimum timing at commercial A/F ratio

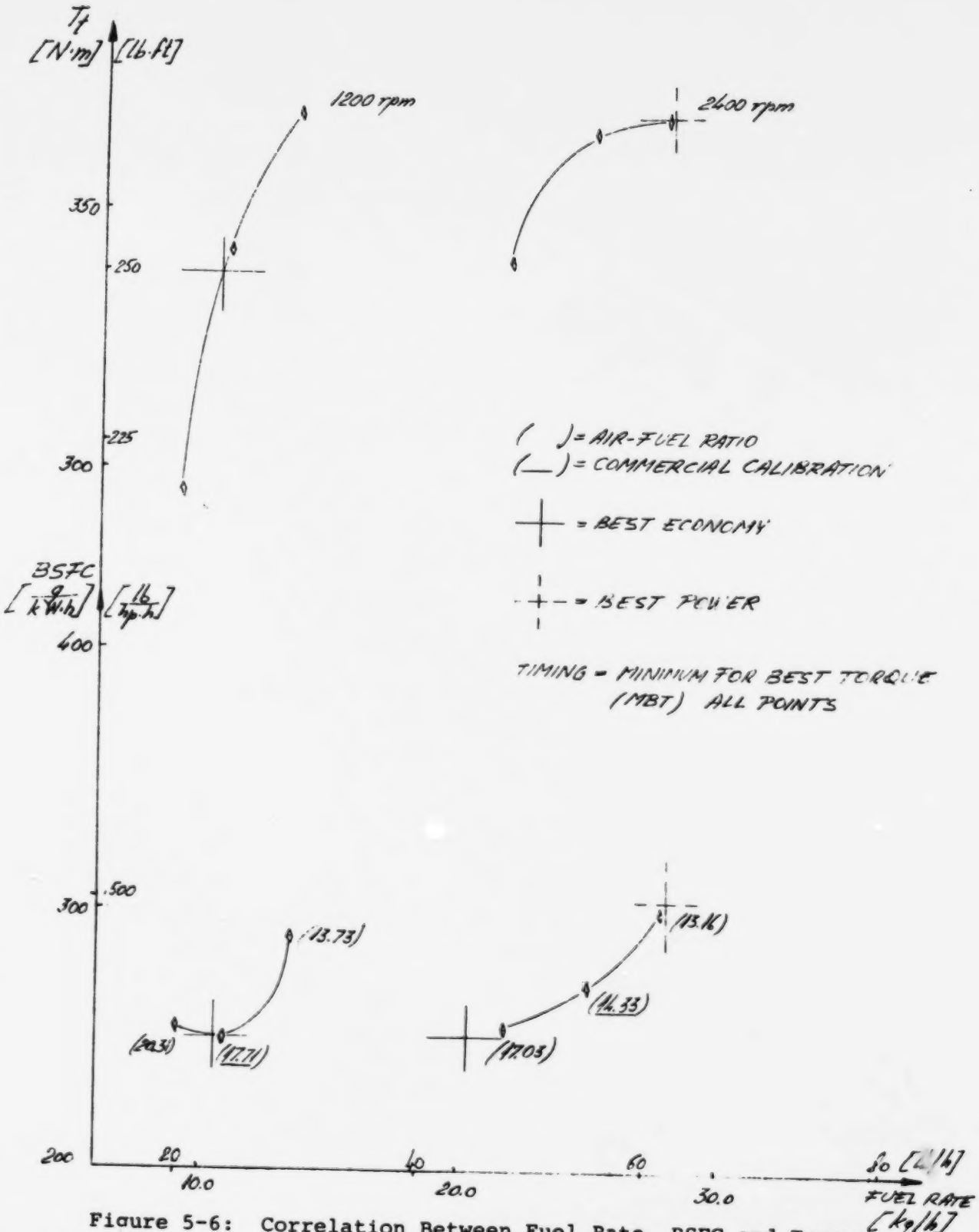


Figure 5-6: Correlation Between Fuel Rate, BSFC and Torque at Different Air-Fuel Ratio; Full Load, FORD 6.1 L LIMA Engine, propane fuel.

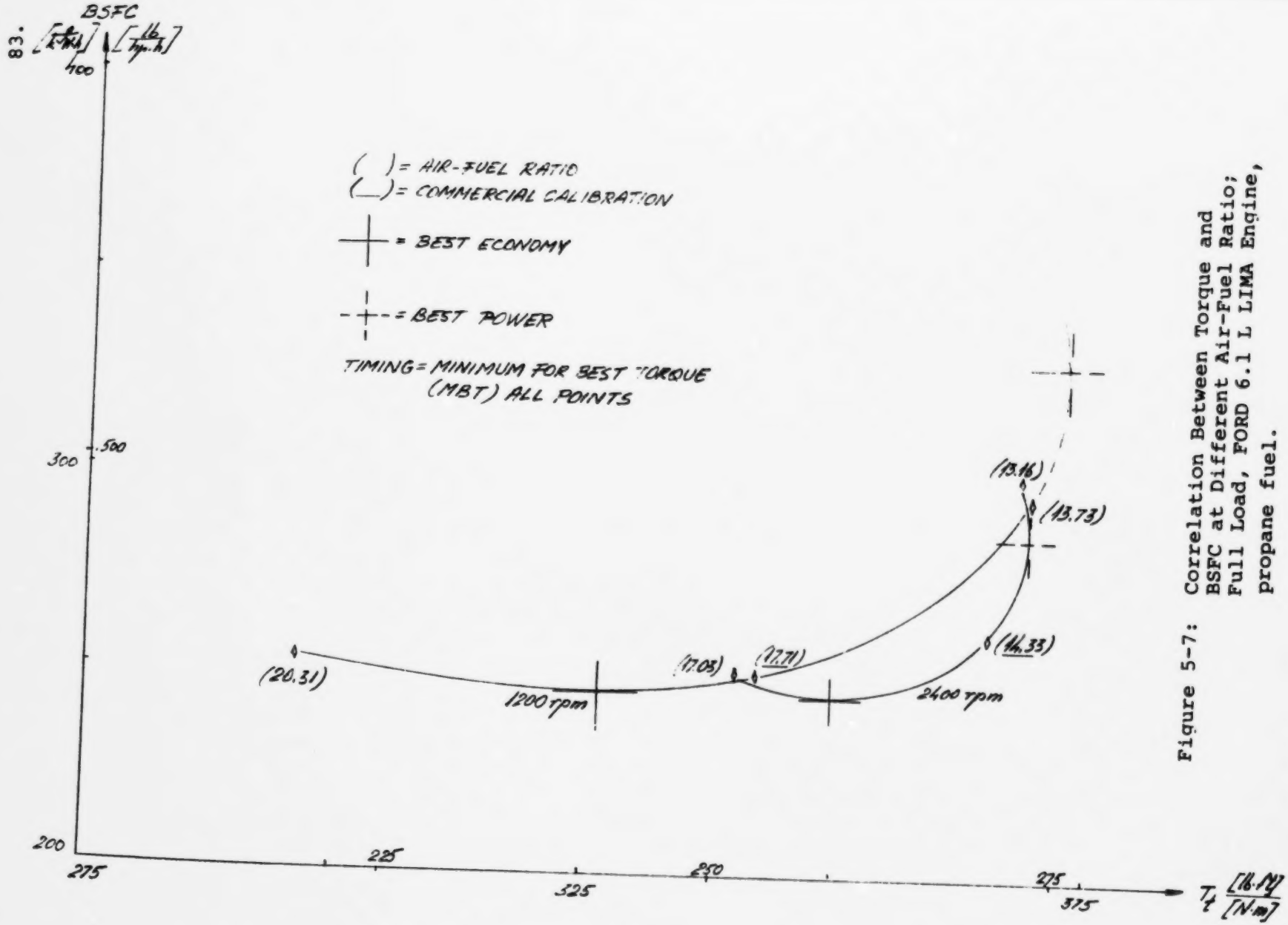


Figure 5-7: Correlation Between Torque and BSFC at Different Air-Fuel Ratio; Full Load, FORD 6.1 L LIMA Engine, propane fuel.

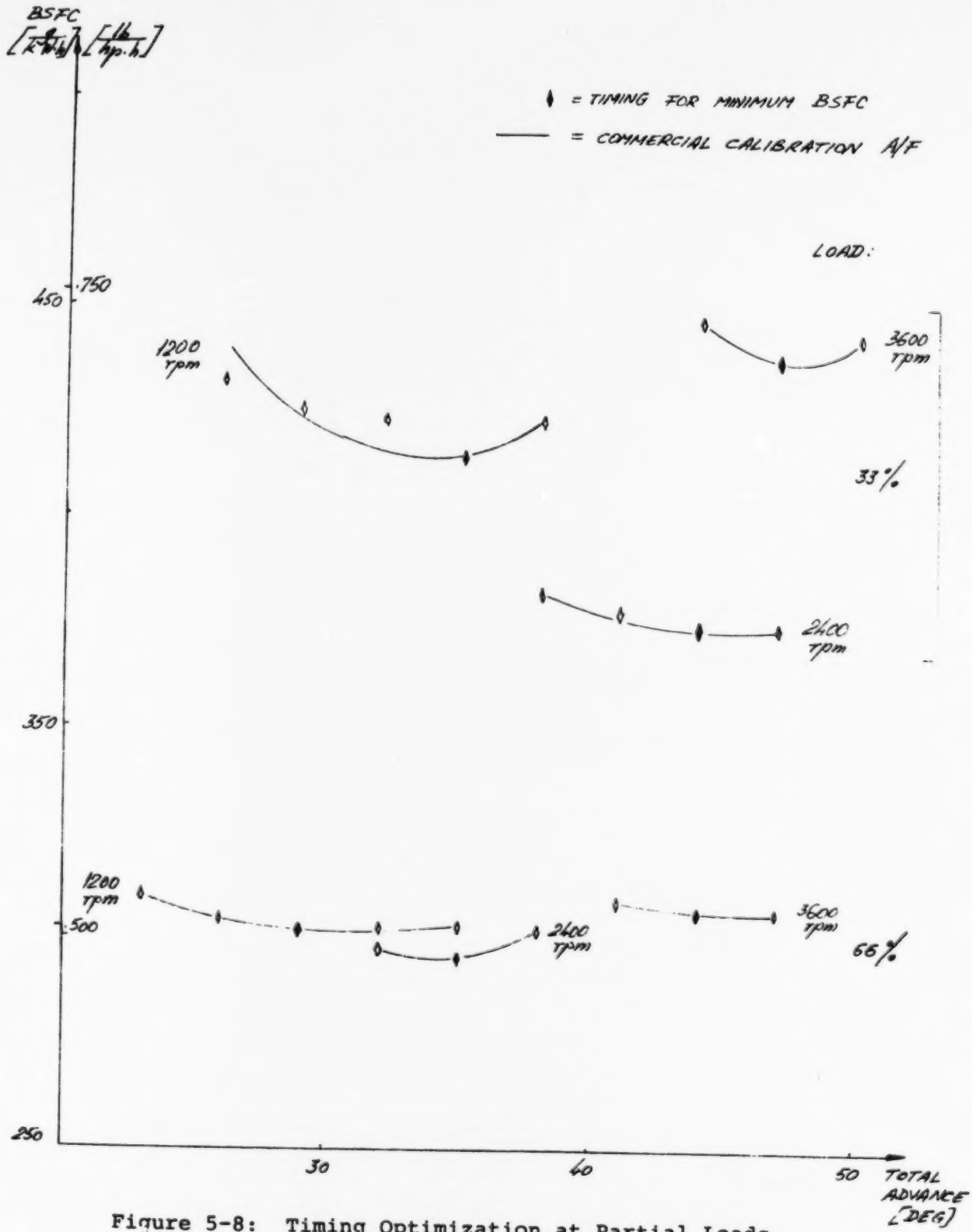


Figure 5-8: Timing Optimization at Partial Loads, for Best Specific Fuel Consumption (FORD 6.1 L LIMA Engine), propane fuel.

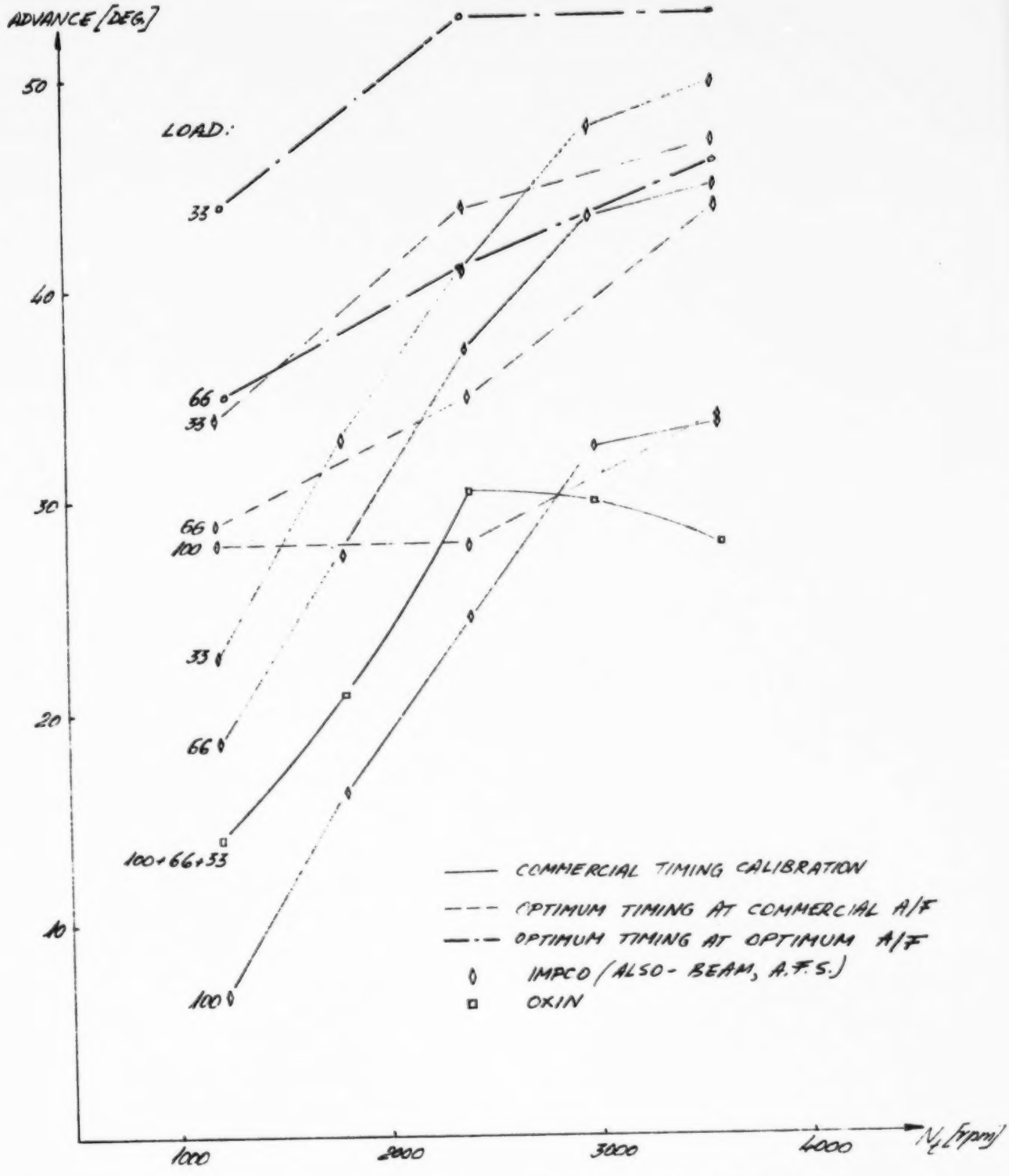


Figure 5-9: Comparison Between Optimum and Commercial Advance, at Constant Air-Fuel Ratio (FORD 6.1 L LIMA Engine), propane fuel.

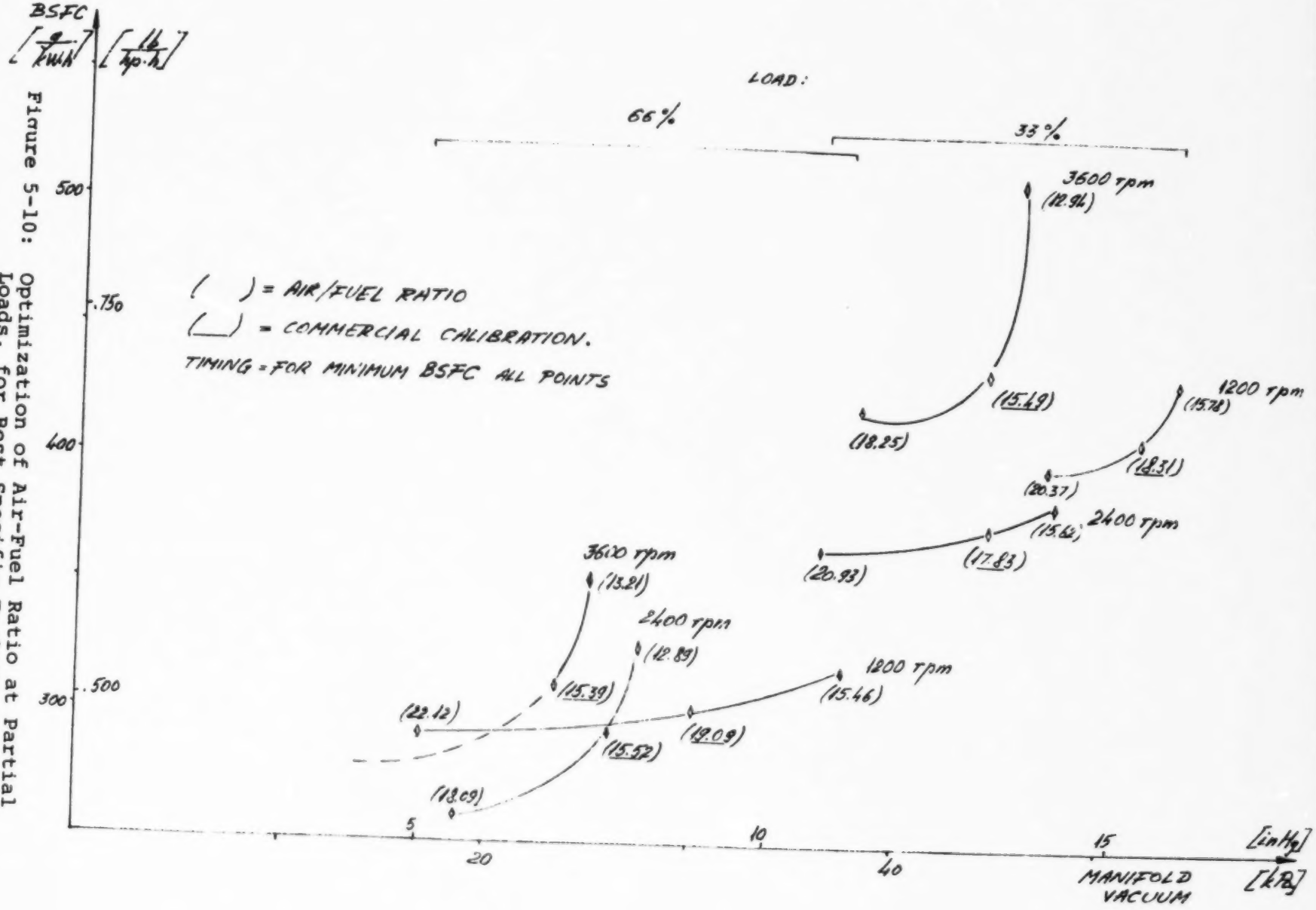


Figure 5-10: Optimization of Air-Fuel Ratio at Partial Loads, for Best Specific Fuel Consumption (FORD 6.1 L LIMA Engine), propane fuel.

Table 5-2: BSFC Optimization at Partial Loads

Engine Speed	rpm	1200		2400		3600	
Load	%	66	33	66	33	66	33
Commercial Calibration BSFC-Mass base (IMPCO syst.)	$\frac{g}{kW.h}$	339.07	468.20	289.43	393.62	332.05	449.75
Optimum BSFC Mass base	$\frac{g}{kW.h}$	292.80	399.70	259.20	365.90	~280.00	422.20
Change vs. Commercial	%	-13.65	-14.63	-10.44	- 7.04	-15.68	- 6.13
Optimum timing	deg.	35	44	41	53	~46	53
Optimum A/F	-	~21.00	20.37	~19.00	20.93	~19.00	18.25

Table 5-3: Improvements in Energy Efficiency [%]

After Timing and A/F Optimization - Partial Loads

Load [%]		Engine Speed [rpm] 1200	2400	3600	Average
66	Before Optimization*	+2.27	+10.82	+ 2.82	
	Improvement	+4.78	+9.10	+18.27	
	Total After Optimizaton	+7.05	+19.92	+21.09	
33	Before Optimization*	+0.94	+12.86	+ 7.79	
	Improvement	+3.41	+4.35	+10.00	
	Total After Optimization	+4.35	+17.21	+17.79	

*Average for 4 systems tested

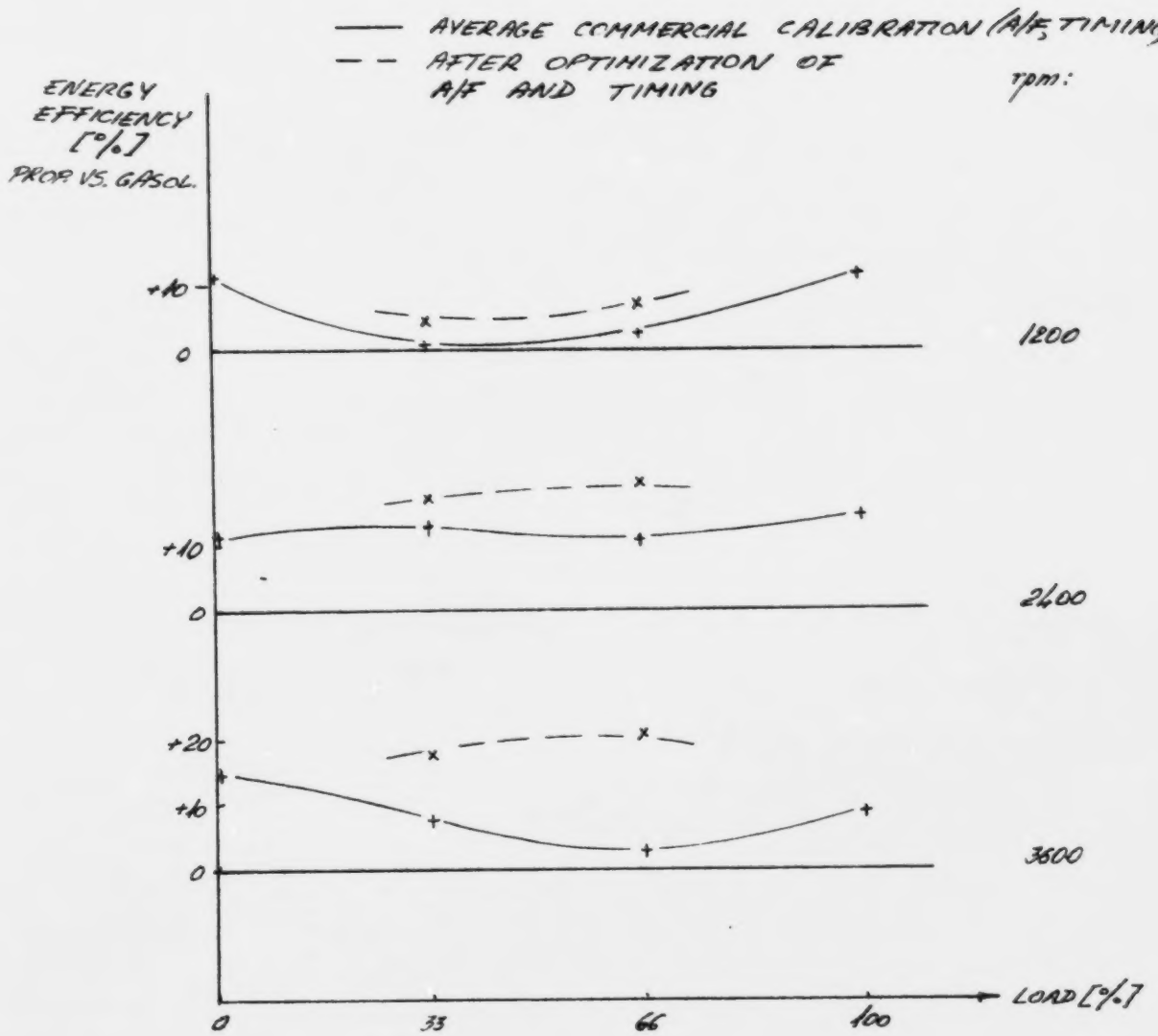


Figure 5-11: Improvement of Energy Efficiency of Propane Carburetion Systems at Partial Loads, After Timing and Air-Fuel Ratio Optimization.

6. CONCLUSIONS

6.1 The maximum power developed with propane at wide open throttle is 0.9 to 3.7% less than for gasoline, for the best "as installed" carburetion systems. Reductions as large as 23.3% were encountered if the commercial settings are too far from optimum values.

6.2 The overall energy efficiency of the best propane system tested is higher by 10.8 to 21.0%, compared to gasoline.

6.3 The increase in volumetric consumption with propane varies from a low of 14.2%, depending on speed and load. The maximum increase was 54.8% for systems running too far from optimum.

6.4 The total spark advance used in this conversion, including the vacuum advance, is closer to the optimum setting and results in better economy than in previous projects.

6.5 The exhaust gas temperatures for gasoline and propane are comparable, depending on the proximity to stroichometric air-fuel mixture and timing.

6.6 The levels of HC and CO are generally lower for propane even without emissions controls. The NO emissions is in many points higher in the absence of the exhaust recirculation valve.

6.7 Use of optimum timing at wide open throttle (WOT) can improve the power output as much as 29.5% in comparison with some conversions as practised now.

6.8 The optimum air-fuel ratio at WOT is 0.925 to 0.935, offering power comparable with gasoline at reasonable fuel consumption.

6.9 The optimization of timing and air-fuel ratio at partial loads -the most important for real driving - results in a supplementary improvement in energy use of 3.4 to 18.3%, if compared with the average of the four systems tested.

7. FUTURE WORK

With the completion of this present phase of the study it can be claimed that a substantial and essentially comprehensive data base has been established concerning the application of propane conversion equipment on light to medium duty internal combustion engines for road vehicles. The experimental study has encompassed five phases, three models of engines and sixteen models of different carburation systems.

The basic raw data and preliminary interpretation of the results are contained in the series of reports ERDL has submitted to MTC. It is appropriate now, however, that the broad experimental investigation has been completed, that an in-depth assessment of the use of propane with optimized add-on carburetor systems be undertaken so that full potential for use as a fuel be exploited.

To this end ERDL proposes the following objectives:

- that all results of the testing program be concentrated in a single source document where information about performance output, fuel economy, emissions characteristics and overall economic impact can be defined,

- that the data base be so constructed that computer modelling of fleet conversion to propane can be initiated,

- that a general methodolgy for propane conversion with optimum performance and fuel economy be formulated,

- and that the experience acquired during the test programs related to the various short-comings of present commercially available propane carburetion systems be documented with a view to propose a new program for the design and testing of an improved system.

The latter objective would integrate into the results of the MTC/ERDL parallel study on natural gas carburetion systems.

Appendix 1

Calculations For Corrected Parameters

$$bp_t = \frac{N_t \times T_t}{9549} \quad (1)$$

bp_t [kW] = brake power, observed at test conditions

T[N.m] = torque, observed

N[rpm] = speed, observed

$$F_t = W_t \times \frac{60}{M} \quad (2)$$

F_t [g/h] = fuel consumption per hour

W_t [g] = mass of fuel consumed during the test

M[min] = test duration

$$bsfc = \frac{F_t}{bp_t} \quad (3)$$

bsfc [g/kW.h] = brake specific fuel consumption

$$bmep_t = 6 \times 10^7 \times \frac{bp_t \times 2}{D \times N_t} \quad (4)$$

$bmep_t$ [kPa] = brake mean effective pressure, observed

D[cm^3] = engine displacement

2 = engine revolutions per cycle, for 4 cycles engine

$$n = \frac{100}{1 + \frac{6.8947 \times x - y \times bmep_t}{bmep_t}} \quad (5)$$

n[%] = mechanical efficiency

$$x = 16.3761 + 2.28629 \frac{N_t}{1000} + 0.297053 \left(\frac{N_t}{1000}\right)^2 \quad (6)$$

$$y = \frac{1}{100} \left[5.44659 - 0.02495 \frac{N}{1000} + 0.174376 \left(\frac{N}{1000}\right)^2\right] \quad (7)$$

$$fp_t = bp_t \left(\frac{100}{n} - 1\right) \quad (8)$$

fp_t [kW] = friction power

$$B_{dt} = B_t - e_t \quad (9)$$

B_{dt} [kPa] = barometric pressure-dry air

B_t [kPa] = measured barometric pressure

e_t [kPa] = water vapour pressure (table).

$$C_s = \frac{97.93}{B_{dt}} \times \sqrt{\frac{t_t + 273}{302.4}} \quad (10)$$

C_s = correction factor for atmospheric conditions

97.93 [kPa] = standard barometric pressure.

302.4 = 29.4 + 273 [°C] = standard temperature

$$bp_c = (bp_t + fp_t) \times C_s - fp_t \quad (11)$$

bp_c [kW] = corrected brake power

$$T_e = \frac{9549}{N_t} \times bp_c \quad (12)$$

T_c [N.m] = corrected torque

$$bmep_c = 1.2 \times 10^8 \times \frac{bp_c}{D.N_t} \qquad (13)$$

$bmep_c$ [kPa] = corrected brake mean effective pressure

APPENDIX 2

Calculation of Air-Fuel Ratio from Exhaust Gas Constituents [1,2,3]

The combustion reaction for a hydrocarbon fuel with air may be expressed as:

$$CHy + (n)O_2 + (3.76n)N_2 \rightarrow (a)CO_2 + (1-a-6c)\ CO +$$
$$+ (b)H_2O + (c)C_6H_{14} + (d)NO +$$
$$+ \left(\frac{y}{2} - b - 7c\right)H_2 + \left(n-a-\frac{1-a-6c}{2} -\right.$$
$$\left. - \frac{b}{2} - \frac{d}{2}\right)O_2 + \left(3.76\ n - \frac{d}{2}\right)N_2 \qquad (1)$$

for one atom of carbon, in which:

( ) = mol of constituents for 1 mol of fuel CH_y (bracketed coefficient)

y = fuel atomic H/C ratio

C_6H_{14} = unburned hydrocarbon, reported as hexane

For a nondispersive infrared (NDIR) analyzer, the term (HC) can be multiplied by a factor of 1.8, to account for the lack of response to certain exhaust HC species (for flame ionization detectors - FID - the factor is 1.0).

Defining a "fuel conversion factor" N:

$$N = \frac{\text{mol exhaust}}{\text{mol fuel}} = \frac{100}{6(HC)+(CO)+(CO_2)} \qquad (2)$$

( ) = molar percent (bracketed species) expressed in [%], and summing the mols of products from eq. (1):

$$N = a+(1-a-6c)+w+c+d\left(\frac{y}{2}-b-7c\right)+\left(n-a-\frac{1-a-6c}{2}-\frac{b}{2}-\frac{d}{2}\right)+\left(3.76\ n-\frac{d}{2}\right) \qquad (3)$$

in which mols of water produced b are replaced by w, mols of water at analyzer, following any condensation. With no condensation, w = b.

$$N = 4.76\ n - 6c + \frac{1-a-6c-3b+y}{2} + w \qquad (4)$$

For the reactants in eq. (1):

$$\frac{\text{mol air}}{\text{mol fuel}} = n+3.76\ n = 4.76\ n \qquad (5)$$

combining eq. (4) and (5)

$$\frac{\text{mol air}}{\text{mol air}} = N+6c-\frac{1-a-6c}{2} + \frac{3b}{2} - \frac{y}{2} - w \qquad (6)$$

and because:

$$\frac{\text{mol X}}{\text{mol fuel}} = \frac{\text{mol X}}{\text{mol exhaust}} \cdot \frac{\text{mol exhaust}}{\text{mol fuel}} = \frac{(X)}{100} \cdot N \qquad (7)$$

Eq. (6) becomes:

$$\frac{\text{mol air}}{\text{mol fuel}} = N+\frac{6(HC)}{100}\cdot N-\frac{(CO)}{200}\cdot N+\frac{3(H_2O)}{200}\ N- \\ - \frac{y}{2} - \frac{(H_2O)a}{100}\cdot N \qquad (8)$$

where $(H_2O)_a$ is water concentration (percent) at analyzers

$$\frac{A}{F} = \frac{\text{g air}}{\text{g fuel}} = \frac{\text{mol air}}{\text{mol fuel}} \cdot \frac{\text{M air}}{\text{M fuel}} \qquad (9)$$

where M refers to molecular weight

$$\frac{A}{F} = \frac{\text{M air}}{\text{M fuel}}\left\{N + \frac{N}{100}\left[6(HC) - \frac{(CO)}{2} + \frac{3(H_2O)}{2} - (H_2O)_a\right] - \frac{y}{2}\right\} \qquad (10)$$

Assuming a fixed value for the water-gas equilibrium

$$k = \frac{(CO)(H_2O)}{(CO_2)(H_2)} = 3.8 \qquad (11)$$

and with

$$(H_2) = \left(\frac{y}{2} - b - 7c\right)\frac{100}{N} = \frac{y}{2}.\frac{100}{N} - (H_2O) - 7\,(HC) \qquad (12)$$

$$(H_2O) = \frac{\frac{y}{2}.\frac{100}{N} - 7(HC)}{\frac{(CO)}{k(CO_2)} + 1} \qquad (13)$$

From eq. (10) and (13) a <u>carbon balance</u> air-fuel ratio can be expressed as:

$$\frac{A}{F} = \frac{M\ air}{M\ fuel}\left[\frac{100+6(HC)-\frac{(CO)}{2}+\frac{3(H_2O)}{2}-(H_2O)_a}{6(HC)+(CO)+(CO_2)} - \frac{y}{2}\right] \qquad (14)$$

in which:

$$(H_2O) = \frac{y[(CO_2)+(CO)]}{2\left[\frac{(CO)}{3.8(CO_2)}+1\right]} \qquad (15)$$

Molecular weights:

M air = 28.96

M fuel = Mc + y M_H = 12.01 + 1.008 y

An <u>oxygen balance</u> independent of the amount of water and diluents is also derived:

$$n = a + \frac{1-a-6c}{2} + \frac{b}{2} + \frac{d}{2} + \left(n-a-\frac{1-a-6c}{2}-\frac{b}{2}-\frac{d}{2}\right) \qquad (16)$$

$$n = \frac{N}{100}\left[(CO_2) + \frac{(CO)}{2} + \frac{(H_2O)}{2} + \frac{(NO)}{2} + (O_2)\right] \qquad (17)$$

$$\frac{A}{F} = 4.76\ n\ \frac{M\ air}{M\ fuel} \qquad (18)$$

$$\frac{A}{F} = 4.76 \frac{M\ air}{M\ fuel} \frac{N}{100} \left[(CO_2) + \frac{(CO)}{2} + \frac{(H_2O)}{2} + \frac{(NO)}{2} + (O_2)\right] \qquad (19)$$

or

$$\frac{A}{F} = 4.76 \frac{M\ air}{M\ fuel} \left[\frac{(CO_2)+\frac{(CO)}{2}+\frac{(H_2O)}{2}+\frac{(NO)}{2}+(O_2)}{6(HC) + (CO) + (CO_2)}\right] \qquad (20)$$

In equations (14) or (20), the molar concentration (HC) is multiplied by 1.8 if the analyzer is nondispersive infrared.

The oxygen balance computation of A/F ratio for 31 samples of exhaust analysis quoted in Table A-1 of Reference [1], resulted in an average error of +0.2352 comparative to measured values of air and fuel mass flows.

For propane (C_3H_8):

$y = \frac{H}{C} = \frac{8}{3} = 2.6667$ and M fuel = $12.01 + 1.008 \times 2.6667 = 14.698$

The values in Chapter 4 are calculated according to eq. (20) and (15).

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2. Stivender, D.L., Kim, Y.C., "Dynamic Computer Techniques for Vehicle Emission Development", SAE Paper 720211.

3. GM Test Code, VI Edition, 1975, pp. 170; "Air-Fuel Ratio Determination from Exhaust Gas Constituents".